

The impact of peripheral mechanisms on the precedence effect

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When two similar sounds are presented from different locations, with one (the lead) preceding the other (the lag) by a small delay, listeners typically report hearing one sound near the location of the lead sound source—this is called the precedence effect (PE). Several questions about the underlying mechanisms that produce the PE are asked. (1) How might listeners' relative weighting of cues at onset versus ongoing stimulus portions affect perceived lateral position of long-duration lead/lag noise stimuli? (2) What are the factors that influence this weighting? (3) Are the mechanisms invoked to explain the PE for transient stimuli applicable to long-duration stimuli? To answer these questions, lead/lag noise stimuli are presented with a range of durations, onset slopes, and lag-to-lead level ratios over headphones. Monaural, peripheral mechanisms, and binaural cue extraction are modeled to estimate the cues available for determination of perceived laterality. Results showed that all three stimulus manipulations affect the relative weighting of onset and ongoing cues and that mechanisms invoked to explain the PE for transient stimuli are also applicable to the PE, in terms of both onset and ongoing segments of long-duration, lead/lag stimuli.

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I. INTRODUCTION

In most environments, a sound propagating directly to a listener is followed by numerous reflections off nearby surfaces, introducing conflicting spatial cues that could make sound localization impossible. Nevertheless, we usually perceive a single, fused sound source at or near the location of the actual sound source. This set of perceptual outcomes, called the precedence effect (PE), is often investigated using headphone presentation of a pair of stimuli (usually clicks) lateralized to different intracranial positions using interaural differences of time (ITD) and level (ILD). The first stimulus, the *lead*, simulates the direct sound. Then, the *lag* is presented after a short delay to simulate a single reflection. Listener outcomes are often measured in terms of *localization dominance*, the degree to which the perceived location of the sound source is dominated by the spatial cues of the lead. Reviews of the PE include Zurek (1987, pp. 85–105), Blauert (1997, pp. 222–237), Litovsky *et al.* (1999), and Brown *et al.* (2014).

While most investigations and explanations of the PE focus on transient, “click” stimuli, many everyday sounds are fairly long in duration, and the PE is observed for these stimuli too. However, Freyman *et al.* (2018) recently showed intriguing evidence that separate explanations may be necessary for the PE with transient versus long-duration stimuli. This calls into question the degree to which measures of the PE based on transient stimuli will predict results for long-duration stimuli. In a previous investigation of the PE for

non-impulsive, long duration noise stimuli presented over headphones, Pastore and Braasch (2015) increased the amplitude of the lag stimulus to probe the effects on localization dominance of offsetting the timing advantage of the lead with a level advantage for the lag. Results showed that localization dominance was robust even when the amplitude of the lag was 6 dB greater than that of the lead, largely consistent with Haas (1972). Results also indicated a strong influence of ILDs produced by physical interference between lead and lag. As lag level was increased, the magnitude of these ILDs decreased—yet, unexpectedly, their effect on perceived lateralization appeared to increase. Furthermore, the degree to which ILDs affected localization dominance varied considerably between subjects, similar to what Braasch *et al.* (2003) found for narrowband stimuli at equal lead/lag levels. In attempting to explain this outcome, Pastore and Braasch (2015) speculated that ITD cues extracted from the onset of the stimulus might result in a robust PE, similar to what might be expected for click stimuli, whereas ITDs extracted from the ongoing stimulus portion might be more variable and thereby lead to a weaker PE that is more susceptible to the influence of ILDs. The authors then hypothesized that inter-subject differences in the degree to which ITD cues from the stimulus onset dominated their overall laterality estimate, called “onset dominance” (OD), might, at least partially, account for the apparent differences in the effects of ILDs on listener performance. Indeed, the degree of OD does appear to vary between listeners (Dietz *et al.*, 2013; Freyman *et al.*, 2010; Freyman *et al.*, 1997; Saberi and Antonio, 2003; Saberi *et al.*, 2004; Stecker and Bibee, 2014 and ITDs appear to be more heavily weighted at stimulus onset whereas ILDs seem to be more evenly

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weighted across the duration of the stimulus (e.g., [Stecker and Brown, 2010](#)).

To begin to consider this hypothesis, we must first understand the role(s) of onset dominance in the PE, and the time scales at which it operates. Furthermore, the mechanism underlying the “ongoing PE” remains largely unidentified, and the applicability, if any, of proposed mechanisms based on transient stimuli is unclear. In order to address these concerns, both targeted, within-subjects testing, and detailed analyses of the ITD and ILD cues available during the onset and ongoing stimulus portions are required.

This study reports behavioral data and simple modeling of relevant peripheral and binaural interactions based on five experiments that probed how mechanisms that result in OD at different levels of processing may contribute to the PE. The first set of experiments (1.1–1.3) aimed at understanding the role of the stimulus onset in eliciting localization dominance and compared performance for long-duration and short, 1-ms duration stimuli. The second set of experiments (2.1–2.2) sought to evaluate the role of the ongoing stimulus portion in localization dominance, and to create a data set that could offer insight into the mechanisms that produce the “ongoing” PE. The same basic testing paradigm presented in [Pastore and Braasch \(2015\)](#) and [Pastore et al. \(2016\)](#) was used, presenting long-duration, lead/lag Gaussian noise burst pairs over headphones and manipulating the intensity of the lag/lead amplitude ratio.

Then, we present simple modeling analyses of the impact monaural, peripheral mechanisms may have on ITDs extracted from the rising envelope slopes of auditory nerve output. We then consider how the outcome of these interactions may impact cue weighting in the formation of a decision variable, ultimately resulting in the laterality estimate for the overall stimulus.

II. METHODS

A. Stimuli

Methods and procedures were identical to [Pastore and Braasch \(2015\)](#) and [Pastore et al. \(2016\)](#). Briefly, six to eleven self-reported normal-hearing listeners, depending on the experiment, participated. The basis of all stimuli was a filtered Gaussian noise created in MATLAB[®]. To simplify modeling of the behavioral results, the same frozen noise seed used in [Pastore and Braasch \(2015\)](#) was used to create all stimuli in all experiments. [Pastore et al. \(2016\)](#) showed that, for the lead/lag stimuli also presented in [Pastore and Braasch \(2015\)](#), the variability of responses to the same token of noise was greater than the variability of responses across different tokens of noise, so the behavioral patterns observed in this study are likely to generalize to other tokens of noise. The noise was generated in the frequency domain, multiplied with a rectangular window and then inverse-Fourier transformed into the time domain to create a noise burst with a center frequency of 500 Hz and a bandwidth of 800 Hz (100–900 Hz). Then, the noise burst was windowed with cosine-squared on- and off-ramps to have the required duration and onset/offset values for that experiment. In this report, stimuli are referred to by their total duration, with the

duration of their onset ramps in subscript. For example, rectangular windowed, 1-ms duration noise bursts are referenced as 1_0 and the 41-ms stimulus with 20-ms cosine-squared on- and off-ramps is referenced as 41_{20} . Stimulus conditions for all experiments are summarized in Table I and Fig. 1. The 1_0 stimuli were created in the same way as the other noise stimuli, but band-pass filtered in the frequency domain between 50 and 3950 Hz. The stimulus was then rectangular windowed in the time domain, resulting in an essentially broadband stimulus. Note that the 1_0 stimuli are nearly the same as the “click” stimuli presented in the headphones studies of [Wallach et al. \(1949\)](#), [Yost and Soderquist \(1984\)](#), and [Xia and Shinn-Cunningham \(2011\)](#), and modeled in [Hartung and Trahiotis \(2001\)](#), amongst many others.

Figure 1 illustrates the basic stimulus configurations. The lead was always presented with an ITD of $\pm 300 \mu\text{s}$ while the lag was presented with an equal and opposite ITD. The delay between the lead and lag, called the *lead/lag delay*, was set between 0–5 ms in steps of 1 ms. Pilot experiments with 200-ms duration stimuli revealed that lead/lag delays longer than 5 ms often induced “split images,” therefore lead/lag delays >5 ms were not tested. The lag/lead amplitude level ratio, called *lag level*, was varied—specific lag levels are listed in Table I. All stimuli were normalized and presented in a sound-isolated booth over Sennheiser HD-600 headphones at approximately 70 dB sound pressure level (SPL), as measured with a Head Acoustics HMS-II.1 artificial dummyhead. For half of the trials, stimuli were presented with the lead ITD favoring the left and the lag ITD favoring the right. ITDs were reversed for the other half of presentations.

B. Procedure

Stimuli were tested in blocks by stimulus type. Within each block, all combinations of lead/lag delay and lag level, shown in Table I, were presented in randomized, counterbalanced order. Each block was completed in approximately 20 min and no more than two blocks were tested for any subject in the same day.

TABLE I. Summary of experimental parameters. Stimuli are referenced by their duration, with their onset duration in subscript, both in terms of ms. Except for the 1_0 rectangular-windowed stimuli, all stimulus onsets and offsets had cosine-squared on- and off-ramps. Rectangular onsets are indicated in subscript by 0. Lead/lag stimuli where the middle portion was extracted, using a diotic window with 20-ms \cos^2 onsets and offsets, are indicated in subscript by $20D$. The range of lead/lag delays and lag levels is given, with the step size between tested lead/lag delays and lag levels in rectangular brackets.

experiment	Duration _{onset} (ms)	Lag levels(dB)	Lead/lag delays (ms)
1.1	$1_0, 41_{20}, 200_{20}$	0–8 [4]	1–5 [1]
1.2	$200_5, 200_{20}$	0–10 [2]	0–5 [1]
1.3	200_{20}	0	0.25–2.25 [0.25]
2.1	$200_{20D}, 200_{20}$	0–10 [2]	0–5 [1]
2.2	$50_{20D}, 100_{20D}, 200_{20D}, 400_{20D}, 600_{20D}$	0	1–5 [1]

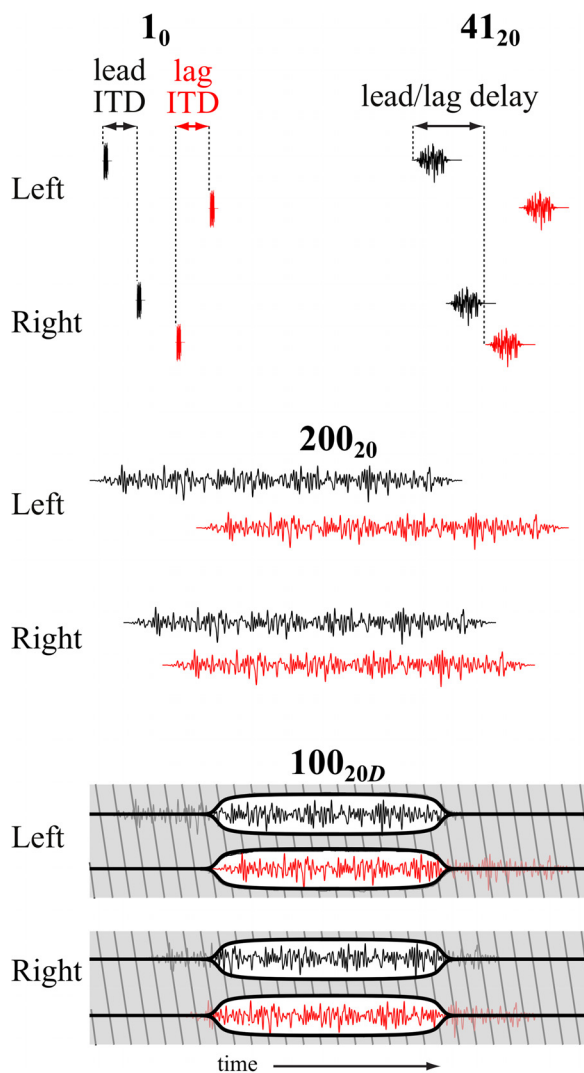


FIG. 1. (Color online) Time domain illustrations, from top to bottom, of the basic types of lead/lag stimuli: 1-ms, 41-ms, and 200-ms noise burst, and an example of the diotically windowed noise burst, this one of 100-ms duration. Lead stimuli are represented in black. The 200- and 41-ms stimuli had a center frequency of 500 Hz with an 800-Hz bandwidth with 20-ms \cos^2 on- and off-ramps. The 1-ms duration stimuli were wideband (50–3950 Hz) Gaussian noises that were then rectangular windowed. The ITD, which was $\pm 300 \mu\text{s}$ for all stimulus conditions, is the delay between the lead (or lag) in one ear and the lead (or lag) in the contralateral ear. The lead/lag delay is the time elapsed between the onset of the lead at one ear and the onset of lag at the other ear. For the diotically windowed stimuli (subscripted 20D) presented in experiments 2.1 and 2.2, a 400-ms duration stimulus was created. Then, the compound lead/lag stimulus was multiplied by a temporally centered diotic window with 20-ms \cos^2 on- and off-ramps. Thick back envelopes indicate the window and hatched gray sections indicate the stimulus portion that was windowed out. This operation yielded a stimulus with a duration of 50–600 ms, depending on the condition, with diotic envelope onsets and offsets but the same ongoing temporal fine-structure relations that would occur in the “ongoing” stimulus portion of the standard long duration lead/lag pairs presented in the earlier experiments. See Table I for further details. Note that ITD and lead/lag delay are not drawn to scale. Also, the ITD was shorter than any stimulus, so the left and right ear signals temporally overlapped for each lead and lag left/right pair.

We employed the same variant of the acoustic pointing procedure introduced by Bernstein and Trahiotis (1985) that we previously reported in Pastore and Braasch (2015). Participants used a trackball mouse to vary the ILD of the pointer so that their perceived intracranial position of the

pointer matched the center of the horizontal, intracranial position from which each perceived sound appeared to originate. The pointer had a 500-Hz center frequency, 200-Hz bandwidth, 20-ms- \cos^2 on/off ramps, and a duration of 200 ms. The ITD of the pointer was 0 ms and the ILD was randomized before each trial. Listeners could play the test stimulus and pointer as many times as they required, with a minimum of three times each before their answer was accepted. Presentations of either target or pointer stimuli were always separated by at least one second. When listeners were satisfied that they had matched their perceived lateral positions of the pointer and test stimulus, they pressed the space bar to record their answer and play the next stimulus.

To compare data across listeners, a “reference” condition was included in which only the lead stimulus was presented with an ITD of 0, +300, or $-300 \mu\text{s}$, in randomized order, 9 times per stimulus. Visual inspection confirmed that listeners perceived all diotic stimuli very close to midline. For analysis and plotting, pointer ILDs were then normalized to facilitate pooling of the data across listeners. For each listener, the pointer ILDs used to match the perceived lateral position of presented stimuli were scaled by the pointer ILDs reported in the reference condition. For example, if a listener indicated their perceived intracranial position of the lead/lag test stimulus using 80% of the ILD they had used to match the position of the single reference stimulus presented with the lag ITD, then their response would be normalized to -0.8 . See the Appendix for details.

For the purpose of discussing the data, we refer to perceived laterality between the midline and the lead position as “localization dominance,” with “stronger” localization dominance signifying responses closer to the lead position (as a matter of convenience, this would also include responses that are further to the lead side than the actual lead ITD) and “weaker” localization dominance signifying responses more toward the midline. Responses between the midline and the lag position would be “failures” of localization dominance.

III. EXPERIMENT 1.1: 1_0 VS 41_{20} VS 200_{20}

A. Rationale

Experiment 1.1 attempted to situate performance for long duration noise stimuli within the context of the transient “click” stimuli used in many previous PE studies. Ten listeners were tested; five had also participated in Pastore and Braasch (2015). Performance was compared for lead/lag stimulus pairs consisting of 1-ms duration, rectangular-windowed noise bursts, often called “clicks,” (1_0), 200-ms duration noise bursts with 20-ms \cos^2 on/off ramps (200_{20}), and an intermediary stimulus which may be conceptualized as a 1-ms click sandwiched between 20-ms \cos^2 on/off ramps, resulting in a 41-ms duration noise burst (41_{20}).

Direct comparison of the 1_0 and 200_{20} stimuli involves several possible confounds. First, since the dominance of ITDs extracted at stimulus onset over ITDs extracted from later stimulus portions is likely to be affected by onset slope, the comparison of performance for the 1_0 and 200_{20} stimuli must take this into account. Indeed, Rakerd and Hartmann (1986) showed that, in an actual room, the PE was maximal

for tonal stimuli with rapid onsets (≈ 0 s), and disappeared entirely at long onsets (≈ 5 s). Second, the rectangular onset of the 1_0 stimulus also introduces high-frequency spectral splatter, whereas the 200_{20} stimulus remains essentially lowpass-filtered below 900 Hz because of its relatively slow 20-ms \cos^2 on/off ramps. In an attempt to disambiguate the relative roles of stimulus duration and the slope of the stimulus onset, the 41_{20} stimulus was also tested. Also, the 41_{20} stimulus allowed an estimation of the effect of the ongoing portion, relative to the onsets, of the 200_{20} stimulus. If onset dominance were complete, then we might expect results for the 41_{20} and 200_{20} stimuli to be essentially the same. If the slope of the onset is of great importance, then we might expect to find a more robust PE for the 1_0 stimuli than for the 41_{20} stimuli.

B. Results

Figure 2 shows the mean normalized response of ten listeners as a function of lead/lag delay; error bars show ± 1 standard error of the mean. The lag/lead level ratio (in dB) is indicated atop each panel. Several differences in listener performance can be seen in the data for the 1_0 stimulus vs the 200_{20} and 41_{20} stimuli.

First, for the 1_0 stimulus, listeners demonstrated localization dominance that is only slightly affected by increased lag level. This is in contrast to the two stimuli with slower onsets (200_{20} and 41_{20}), which steadily shift towards the lag ITD with increased lag level. Responses to the 200_{20} stimulus show a non-monotonic oscillation across lead/lag delays that increases in its depth with increased lag level, as previously reported in Pastore and Braasch (2015). This pattern does not appear in responses to the 1_0 stimulus.

Another difference in performance for the 1_0 stimulus vs the 200_{20} and 41_{20} stimuli is observed at 1-ms lead/lag delay. For the 0-dB and 4-dB 200_{20} stimulus conditions, listeners indicated lateral positions that “overshoot” the lead position. Even at 8-dB lag level, lateralization was halfway between the midline and lead positions, while results for the

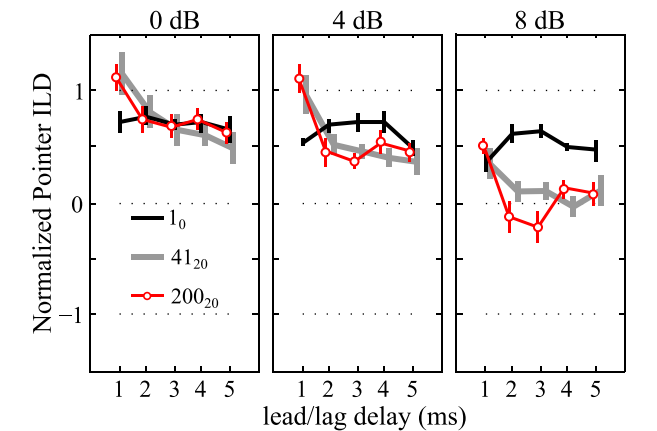


FIG. 2. (Color online) Normalized performance of six listeners for the 1_0 , 41_{20} , and 200_{20} stimuli. The ILD of the acoustic pointer was normalized such that +1 indicates perceived lateral position that was the same as for the lead presented alone (without the lag), -1 matching the lag alone, and 0 matching diotic presentation. The lag/lead level ratio is indicated above each figure panel. For legibility, data points for different stimulus conditions are skewed slightly to the left and right of each other.

other lead/lag delays were near midline or towards the lag side. A similar pattern at 1-ms lead/lag delay was observed for the 41-ms stimulus at all lag levels. This trend was not evident for the 1_0 stimulus.

In general, as lag level was increased, the difference between the 1_0 stimulus and the longer duration, slower onset stimuli increased. That is, the data for the 1_0 stimuli serve as an increasingly poor predictor of performance for both the 41_{20} and 200_{20} stimuli as lag level is increased. Also, for the 0 and 4 dB lag level conditions, the difference between the 41_{20} and 200_{20} stimuli was very little, and small differences only emerged at 8 dB for 2- and 3-ms lead/lag delay. Increased lag level was expected to draw out different performance at different lead/lag delays for the three stimuli, and so paired t-tests were done between stimuli for all conditions. Details of these statistical analyses are presented in Table II—the general trend is that differences in performance between the 1_0 stimulus vs the two other stimuli are few for lag levels of 0 and 4 dB, and considerable at 8 dB. Performance for the 41_{20} and 200_{20} is essentially the same.

C. Discussion

Hartung and Trahiotis (2001) and later Xia and Shinn-Cunningham (2011) have shown that monaural, peripheral auditory processes can explain a great deal of data for PE experiments using click stimuli. In addition, Tollin and Henning (1998) and Hartung and Trahiotis (2001) have shown that “ringing” of the basilar membrane can lead to interference patterns on the basilar membrane for successive lead and lag binaural transients that can introduce binaural cues that were not in the original stimulus. One might expect that performance for long-duration lead/lag stimuli could be predicted on the basis of results already obtained with click stimuli. The data presented here suggest that this is not entirely the case. Surprisingly, within-subjects variability (not shown) was often considerably greater (as much as twice at some lead/lag delays) for the 1_0 stimuli than for the other two stimuli, suggesting that the ongoing portion of the stimulus might offer additional information that can be integrated and compared with cues from the stimulus onset for a

TABLE II. Results of paired t-tests. A Bonferroni correction is applied to the significance criterion, $\alpha = 0.05/2 = 0.025$ because each condition is involved in two comparisons. Values are shown when $p < 0.025$. None of the 41_{20} vs 200_{20} comparisons were significant, so they are not shown.

Comparison	Lead/lag delay (ms)	Lag level (dB)		
		0	4	8
1_0 vs 200_{20}	1	0.0017	0.0004	—
	2	—	—	0.0008
	3	—	0.0146	0.0014
	4	—	—	0.0040
	5	—	—	0.0130
1_0 vs 41_{20}	1	—	—	—
	2	—	—	0.0008
	3	—	0.0067	0.0007
	4	—	0.0043	0.0004
	5	—	—	0.0017

more stable estimate of laterality. This idea is tested further in experiment 2.2.

These differences between 1_0 stimuli and the two other, longer duration stimuli are likely to result, in part, because of additional factors that come into play with longer duration noise stimuli. First, while the 1_0 stimuli produce ringing on the basilar membrane that can lead to interference between lead and lag, long-duration stimuli temporally overlap, so that physical interference effects can create ILDs before the stimulus even reaches the basilar membrane. Together they may result in binaural cues that are different to those elicited by the 1_0 stimulus. Second, [Dizon and Colburn \(2006\)](#) showed that the ongoing, temporally overlapping portion of long-duration noise stimuli can elicit the PE even when the onset and offset portions of stimuli are diotically windowed out. [Braasch and Blauert \(2003\)](#) tested the model of [Hartung and Trahiotis \(2001\)](#) and found that it did not predict listener performance for long-duration stimuli presented in [Braasch et al. \(2003\)](#), suggesting that, for long-duration stimuli, the PE could be a result of interactions that occur at both the onset and the ongoing portions of the stimulus—see also [Freyman et al. \(2010\)](#). Relatedly, [Freyman et al. \(2018\)](#) show evidence that the peripheral interactions that predict the PE for clicks do not appear to account for the PE in the “ongoing PE” that occurs for their lead/lag click-train stimuli. If this analysis is correct, then we might expect to see different performance for the 1_0 stimulus and longer duration stimuli, especially as lag level is increased and the underlying mechanisms are pushed to their limits.

IV. EXPERIMENT 1.2: THE EFFECT OF A FASTER ONSET FOR LONG-DURATION STIMULI

A. Rationale

Two important differences between the 1_0 and 200_{20} stimuli in experiment 1.1 were their frequency content and onset ramps. While the 1_0 was broadband, the 200_{20} stimulus was band-limited between 100 and 900 Hz. To investigate what effect, if any, these commingled factors might have had in driving the results of experiment 1.1, experiment 1.2 presented stimuli with a 200-ms duration, but shortened the

onset ramp to 5-ms \cos^2 (referenced as 200_5), so that the relative effect of a faster onset could be measured while limiting spectral splatter to maintain nearly the same frequency content as the 200_{20} stimulus. It may be that localization dominance was stronger for the 1_0 because there are more bands over which to integrate—the present experiment controls for this. We expected the faster onset slope to elicit greater onset dominance for the 200_5 stimulus than the 200_{20} stimulus, resulting in localization dominance that would be more robust to the effects of ILDs generated by the physical interference of lead and lag.

B. Results

Figure 3 shows the results for the six listeners. As expected, lateralization was, on average, further toward the lead for the 200_5 stimulus than for the 200_{20} condition. Also, there was a less pronounced “dip” at 3 ms lead/lag delay, suggesting that the faster onset resulted in localization dominance that was more robust to effects of ILDs generated by interactions between lead and lag.

Pairwise t-tests across all listeners comparing the 20-ms onset control and 5-ms onset conditions for all combinations of lead/lag delay and lag level reveal that they are significantly different ($\alpha = 0.05$) at all lag levels for lead/lag delays of 2, 3, and 4 ms. Only two lag level conditions were significantly different for lead/lag delays of 1 (6 and 10 dB) and 5 ms (0 and 2 dB). Comparing the individual listener data for the 5-ms and 20-ms onset conditions (not shown), the more rapid 5 ms onset resulted in stronger localization dominance for most listeners, with a proportionally larger “benefit” as lag level was increased. Variability for the 200_5 stimulus was lower than for the 200_{20} stimulus for the majority of lead/lag delays for lag levels greater than 0 dB. A partitioning of variability (see [Pastore et al., 2016](#), for details on the method) revealed that nearly all of the reduction in variability for the faster stimulus onset came from reduced trial-to-trial variation in listener responses, not reduced differences between subjects.

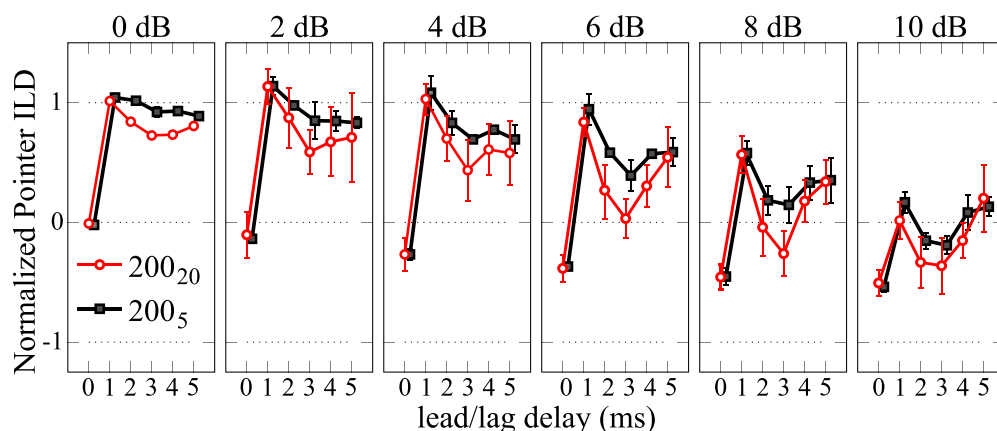


FIG. 3. (Color online) The normalized performance of 6 listeners for the 200_{20} (open circles) and 200_5 (filled squares) conditions. Vertical bars show the standard error of the mean. Figure is otherwise read the same as Fig. 2.

V. EXPERIMENT 1.3—THE TIME WINDOW FOR ONSET EFFECTS: SUMMING LOCALIZATION

A. Rationale

As mentioned by [Hartung and Trahiotis \(2001\)](#), the range within which monaural, peripheral interactions are likely to play an important role in the PE is limited to be “effectively shorter than the reciprocal of the bandwidth of the auditory filter being stimulated” ([Trahiotis and Hartung, 2002](#)). There is likely to also be some limit to how short the lead/lag delay can be for filter ringing and adaptation to have enough time to occur before the lag arrives, possibly resulting in reduced localization dominance. Summing localization, a phenomenon closely related to the precedence effect, occurs at lead/lag delays below ≈ 1 ms—listeners typically report a single fused sound source located at some compromise position between the lead and lag. Experiment 1.3 exploited the possibility that summing localization is, in part, the result of a decreased effect of these monaural, peripheral interactions. If ITD onset dominance is weakened by too short a lead/lag interval, then we would expect inter-fererence ILDs to have an outsized effect on lateralization.

Listeners’ perceived auditory lateralization was tested for small lead/lag delays from 0 to 2.25 ms in steps of 0.25 ms. This range of lead/lag delays enabled a direct comparison of the effect of ILDs on listeners’ performance under conditions known to evoke summing localization and the PE. Subjects were 6 males and 1 female, ages 24–42. All were self-reported as normal hearing and have extensive experience with listening tests including [Pastore and Braasch \(2015\)](#). Stimuli were identical to the 200₂₀ condition. Lead and lag stimuli were equal intensity for all presentations.

B. Results

Figure 4 shows the results for experiment 1.3 averaged across 7 listeners. Surprisingly, the data do not show a linear transition from summing localization to localization dominance, suggesting that ITD-based onset dominance is quite weak at very short lead/lag delays. Although the general trend does move towards the lead, very short lead/lag delays of 0.25 ms and 0.50 ms are actually lateralized to the side of the lag. At a lead/lag delay of 1-ms the auditory event is lateralized further towards the lead side than was the lead when it was presented in isolation. At lead/lag delays of 1.25 and 1.5 ms further oscillations can be seen, with the auditory event being lateralized less to the direction of the lead than for lead/lag delays of 2 and 2.25 ms.

C. Discussion

The inset in Fig. 4 is a plot that shows broadband ILDs created by the physical interference of lead and lag in the left and right channels as a function of lead/lag delay. The covariation of listeners’ responses with the pattern of ILDs is readily apparent. The fact that listeners’ perceived lateralization of the stimulus is to the lag side for the two shortest lead/lag delays supports the hypothesis that the onset cue would be weaker for very short lead/lag delays. Using 1-ms duration “clicks” (essentially the same as the 1₀ stimulus),

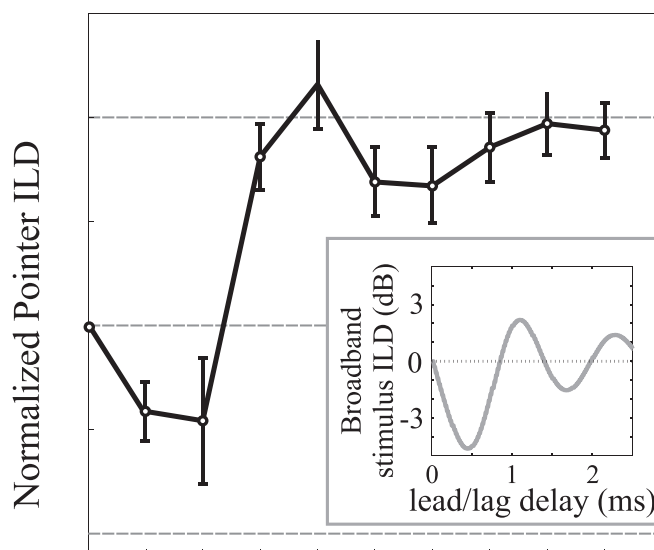


FIG. 4. The performance of 7 listeners for 800-Hz bandwidth 200-ms Gaussian noise bursts in the presence of one lag stimulus. Figure is otherwise read the same as previous data figures. Inset: Calculated broadband interaural level differences as a function of lead/lag delay.

[Zurek and Saberi \(2003\)](#) tested lead/lag delays of 0.3 and 0.6 ms, but did not report lateralization to the lag side for either stimulus condition. However, [Tollin and Henning \(1999\)](#) showed results for 20- μ s duration click stimuli that demonstrate a very similar ILD effect, in that case due to interference patterns of ringing on the basilar membrane, despite no temporal overlap of the stimuli themselves. It seems likely that the pattern of the data in our present experiment is therefore the result of both physical interference of lead and lag and monaural interactions on the basilar membrane of lead and lag suggested by [Tollin and Henning \(1999\)](#) and [Hartung and Trahiotis \(2001\)](#).

VI. EXPERIMENT 2.1: THE EFFECT OF REMOVING GATING ONSETS

A. Rationale

Experiments 1.1–1.3 measured the role of the stimulus onset in the PE. The degree to which localization dominance in experiment 1.1 was “strengthened” or “weakened” by the inclusion of a long-duration, temporally overlapping stimulus portion—the 200₂₀ stimulus—clearly varied between listeners. Experiments 2.1 and 2.2 probed the role of the ongoing stimulus portion in the PE.

[Dizon and Colburn \(2006\)](#) did just this, measuring the relative frequency at which listeners demonstrated perceived lateralization to the lead side for several bandwidths of 500-ms duration lead-lag noise pairs, but with an interesting modification: the onsets were diotically windowed with 20-ms \cos^2 onsets and offsets so that there was no gating delay between the lead and lag, even while the fine structure delay remained. For Gaussian noise, lowpass filtered at 1500 Hz, [Dizon and Colburn \(2006\)](#) stated that listeners perceived sound sources to the side of the lead at well-above chance levels for lead/lag delays of up to approximately

20 ms. Neither the lateral extent of localization dominance nor the degree of fusion were reported. This intriguing and important result begs further questions. When listeners' perceived intracranial lateralization was to the side of the lead, was the lateral extent the same for stimuli with diotically windowed onsets and offsets as for those with onset and offset cues intact? If there is a difference, can the effect of the cues at stimulus onset and offset be partitioned from those of the ongoing cues? Finally, does the variability between subjects found in experiment 1 persist, and how is listener performance for the 200₂₀ condition correlated with lateralization of stimuli with diotically windowed onsets and offsets?

Experiment 2.1 investigated the role of the ongoing portion of lead/lag noise stimuli by using a diotically gated stimulus envelope, similar to that used in [Dizon and Colburn \(2006\)](#), but with several added features. First, the delay between lead and lag was set, in pilot experiments, to <5 ms so that all stimuli would be very likely to elicit fused percepts. Second, the lateral position of listeners' perceived auditory events was recorded with an acoustic pointer. Third, the degree to which localization dominance was robust to increased lag level was tested for comparison with stimuli with dichotic 20-ms cos² on/off ramps. In the first condition, all listeners were presented the same 200₂₀ stimulus that was presented in [Pastore and Braasch \(2015\)](#). In the second condition, a similar stimulus was presented, but with onsets and offsets removed, using a diotic window with 20-ms cos² onsets and offsets, so that only a 200-ms duration temporally overlapping segment of the compound stimulus remained (referred to as 200_{20D})—see Fig. 1 and Table I for further details.

B. Results and discussion

Figure 5 shows the averaged, normalized pointer ILDs used by 11 listeners to match their perceived lateralization of the 200_{20D} and 200₂₀ stimuli. The figure is read the same as the three previous results figures. Two main patterns in listener performance emerge. With a few exceptions, lateralization is more to the midline for the 200_{20D} than the 200₂₀ stimuli, suggesting reduced localization dominance

and a weaker PE. For the 200_{20D} condition at lead/lag delays greater than 3 ms, listeners demonstrate localization dominance that is much weaker and essentially fails at lag levels of 2 dB and greater. Nevertheless, for lead/lag delays of 1–3 ms, listeners demonstrate localization dominance that is weaker but still comparable to that for the 200₂₀ condition.

Paired t-tests for all lag level and lead/lag delay stimulus combinations reveal that, for all lead/lag delays greater than 1 ms, comparisons between the 200₂₀ and 200_{20D} conditions are significant at all lag levels except the 3 ms condition for lag levels of 0 and 2 dB. [Pastore and Braasch \(2015\)](#) showed that ILDs around 750 Hz appeared to have a strong effect on perceived lateralization of the 200₂₀ stimulus. The middle 200 × 48 000 samples (i.e., 200 ms of noise) of the first 400 × 48 000 samples were used for the 200_{20D} stimulus, whereas the first 200 × 48 000 samples of the same noise token were used for the 200₂₀ stimulus, so ILDs were somewhat different for the two stimuli. Analysis (not shown) revealed that the pattern of ILDs generated by the physical interference of lead and lag centered around 750-Hz for the 200_{20D} stimulus favored the lag side at 2-ms lead/lag delay while the ILD at that frequency was nearly 0 for the same lead/lag delay with the 200₂₀ stimulus. Likewise, while the ILD around 750 Hz was quite small for the 200_{20D} stimulus at 3-ms lead/lag delay, there was a relatively large ILD favoring the lag for the same 200₂₀ condition. This may help explain the reduced localization dominance at 2-ms lead/lag delay and enhanced localization dominance at 3-ms lead/lag delay for the 200_{20D} stimulus as compared to the 200₂₀ stimulus. For the 1-ms lead/lag delay conditions, differences are significant for lag levels above 6 dB and not so for lag levels below 6 dB. A large ILD pointing to the lead side for the 1-ms lead/lag delay condition was found for the 200₂₀, 200₅, and 200_{20D} stimulus conditions (see Fig. 4 for broadband ILDs and [Pastore and Braasch, 2015](#), for an analysis within auditory filters), so the similarity in listener performance at 1-ms lead/lag delay is not surprising.

In general, most listeners performed similarly to the average result, though between-subjects variability was considerable. A partitioning of variability (not shown) indicated

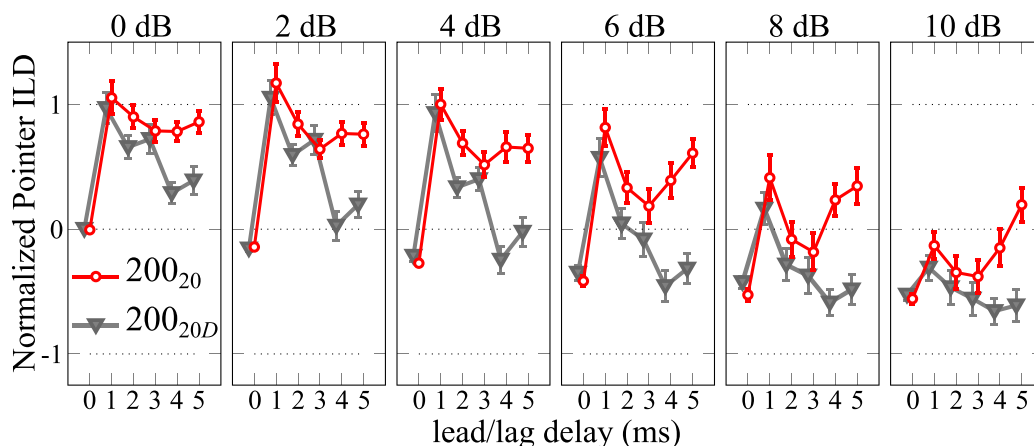


FIG. 5. (Color online) Normalized listener performance for the 200₂₀ (open circles) vs 200_{20D} (downward triangles) conditions for 11 listeners. See Table I and Fig. 1 for further details.

essentially equivalent levels of within- and between-subjects variability for both the 200₂₀ and 200_{20D} stimuli.

Figure 6 recasts the same data in terms of the average difference in lateralization from listeners' response to the 200₂₀ control stimulus for the 200₅ and 200_{20D}, so that between-subject differences do not obscure the effects of the stimulus conditions. Positive values indicate perceived lateralization further towards the lead (greater localization dominance) than was observed for the 200₂₀ control stimulus. Negative values indicate perceived lateralization further to the direction of the lag (less localization dominance). The horizontal dotted line at zero indicates performance that was the same as the control. The reduced localization dominance when onsets were diotically windowed, and the increased localization dominance when the onset was made 15-ms faster, can be clearly seen for most combinations of lead/lag delay and lag level. Interestingly, for the 5-ms lead/lag delay condition, diotic onsets resulted in a large decrease in localization dominance but a faster onset seems to have led to no real increase in localization dominance. As shown in ILD analyses in [Pastore and Braasch \(2015\)](#), there is no particularly large ILD pointing to either the lead or the lag at this lead/lag delay, as there was at 1-ms lead/lag delay for all 3 stimuli. Furthermore, performance at 5-ms lead/lag delay was essentially the same for the 200₂₀ and 41₂₀ stimuli tested in experiment 1.1, and localization dominance was far weaker for the 200_{20D} condition at this lead/lag delay, so it is clearly not the case that performance was driven by the ongoing portion of the stimuli. We cannot currently explain why the faster 5-ms onset had an effect on lateralization at the 2-, 3-, and 4-ms lead/lag delays but not at 5-ms lead/lag delay.

VII. EXPERIMENT 2.2: THE EFFECT OF DURATION ON STIMULI WITH DIOTICALLY GATED ONSETS AND OFFSETS

A. Rationale

Experiment 2.2 tested the effect of stimulus duration for the diotically windowed stimulus condition (i.e., 200_{20D}) investigated in experiment 2.1. [Dizon and Colburn \(2006\)](#)

presented 500-ms duration stimuli, whereas the current group of experiments used 200-ms duration stimuli. The effect, if any, that this difference in stimulus duration had between the two experiments was therefore of interest. Despite removing the *gating onset differences* between left and right channels for the 200_{20D} stimulus, the onset has clearly not been “removed.” That is, there nevertheless remains a diotic gating onset with dichotic fine structure that may or may not suggest a position in the center. In keeping with the longer-term onset dominance observed for the 200₂₀ and 200₅ stimuli, it seems plausible that listener responses to the 200_{20D} could therefore also be driven primarily by the (diotic) onset of that stimulus. If this onset were to dominate perceived laterality of the entire stimulus, we would expect that behavior would be largely the same regardless of stimulus duration, similar to the comparison between the 200₂₀ and 41₂₀ stimuli in experiment 1.1. An alternative hypothesis is that the spatial cues in the 200_{20D} stimulus are highly ambiguous, especially at stimulus onset, given the diotic gating window, so that perceived location must be integrated over a longer duration in order to lower uncertainty. This theory of the ongoing PE mechanism would be supported with the diotic onset/offset stimuli if we were to observe increased localization dominance as a function of increased stimulus duration. As such, an understanding of the temporal integration window necessary to elicit localization dominance for stimuli with diotic on/off ramps is essential to an eventual understanding of the mechanisms involved in any putative “ongoing PE mechanism.”

B. Results

The results, averaged across six listeners, are shown in Fig. 7(A). While it is clear that increased stimulus duration elicits greater localization dominance for all lead/lag delays, most of the gain in the lateral extent of listener responses appears to occur by 200-ms stimulus duration. This observation is confirmed in Fig. 7(B), which shows the change in responses as a function of increasing the stimulus duration beyond 50 ms, averaged across lead/lag delays and listeners. Error bars show the average standard error of the mean across

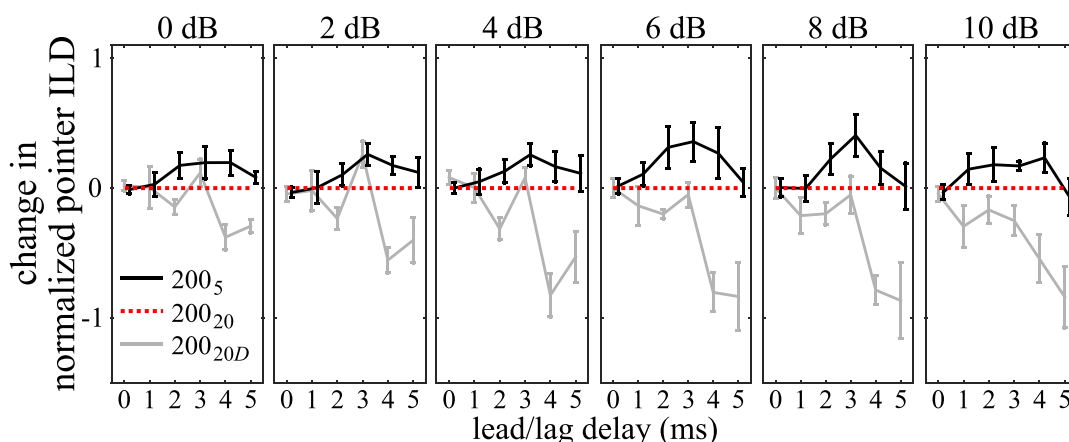


FIG. 6. (Color online) The mean and standard error of the mean of the change in lateralization, relative to the 200₂₀ condition, for the six listeners (shown also in Fig. 3) who participated in the 200₂₀, 200₅, and 200_{20D} conditions. Black lines show the change resulting from sharpening the onset to 5 ms and gray lines show the change resulting from diotically windowing onsets and offsets.

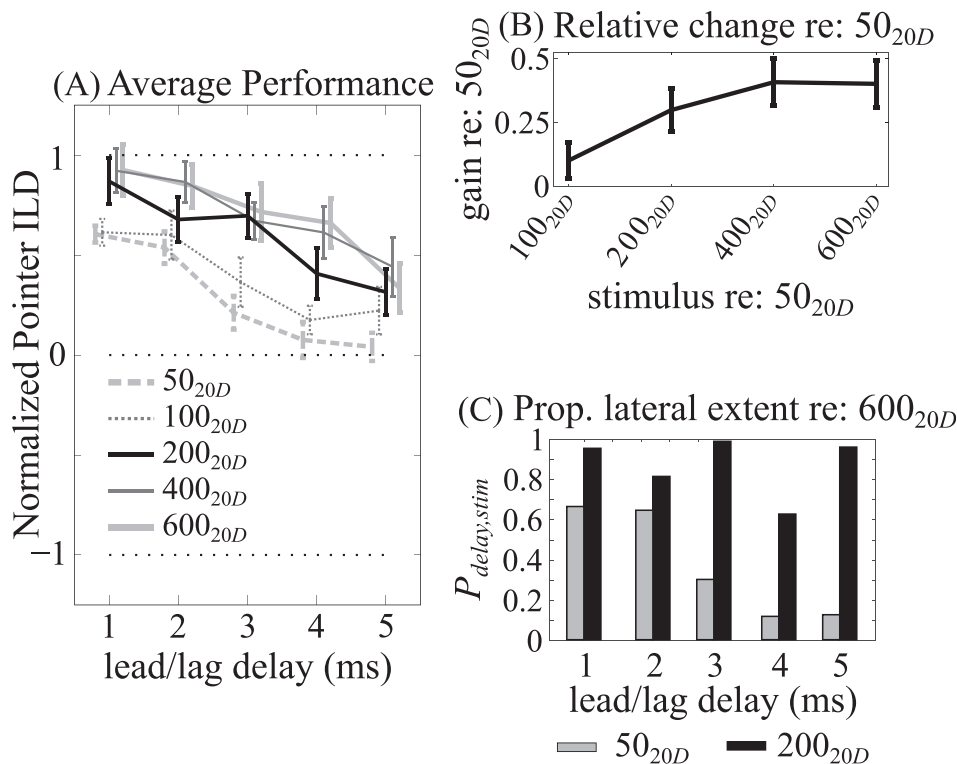


FIG. 7. (A) The average performance of 6 listeners for stimuli of various durations with diotic onsets and offsets. Vertical bars indicate the standard error of the mean. (B) The mean change, averaged across lead/lag delays and listeners, in lateralization re: the 50_{20D} condition for each longer duration stimulus. Error bars indicate the standard error of the mean averaged across lead/lag delays. Positive values indicate responses that are further towards the lead than for the 50_{20D} condition. (C) The proportion of the lateral extent reported for the 600_{20D} condition that was reported for the 50_{20D} (gray bar) and 200_{20D} (black bar) conditions.

lead/lag delays. Increasing stimulus duration to 200 ms resulted in lateralization that was further toward the lead position at all lead/lag delays, but further increases in duration yielded only small gains in localization dominance, if any.

Looking again at the data in Fig. 7(A), listeners reported perceived lateralization toward the lead position for even the shortest (50- and 100-ms) stimulus durations for lead/lag delays of 1 and 2 ms. By contrast, lateralization for the 4- and 5-ms lead/lag delays was, at most, midway between the midline and the lead position for the longest duration stimuli and close to midline for the two shortest stimuli. In other words, both increased lead/lag delay and decreased stimulus length appear to result in decreased localization dominance. The analysis in Fig. 7(C) probes this interaction—it asks the question (lead/lag delay, is notated here as “delay”), “what proportion, $P_{delay,stim}$, of the maximal lateralization toward the lead (i.e., the degree of localization dominance measured for the 600_{20D} condition, $L_{delay,600_{20D}}$) was reported for the shortest, $stim = 50_{20D}$ condition (gray bars) or the longer $stim = 200_{20D}$ (black bars) condition tested in experiment 2.1?” $P_{delay,stim}$ is calculated as $P_{delay,stim} = L_{delay,stim} / L_{delay,600_{20D}}$.

For lead/lag delays of 1 and 2 ms, $P_{delay,50_{20D}}$ was an average of 64.43%, while for lead/lag delays of 3, 4, and 5 ms, $P_{delay,50_{20D}}$ was an average of only 17.6%. That is, for the two shortest lead/lag delays, $P_{[1,2],50_{20D}}$ was ≈ 3.5 times $P_{[3,4,5],50_{20D}}$. On the contrary, for the 200_{20D} stimulus (also tested in experiment 2.1), lead/lag delay had little effect; the average of $P_{delay,200_{20D}}$ for the 1- and 2-ms lead/lag delay conditions was 87.5% and nearly the same for lead/lag delays of 3, 4, and 5 ms at 84.5%. The analyses in Fig. 7(C) show that, for short lead/lag delays (1–2 ms), the early portion of the diotic onset/offset stimulus was largely sufficient for listeners to demonstrate fairly robust localization dominance. However, for longer lead/lag delays (3–5 ms) they required a

considerably longer stimulus to generate even the comparatively weaker localization dominance demonstrated for these longer lead/lag delays.

A paired t-test comparing perceived lateralization across all listeners for each lead/lag delay at stimulus durations of 200 and 600 ms revealed that the 1-, 3-, and 5-ms lead/lag delay conditions were not significantly different, while the 2- and 4-ms lead/lag delay conditions were ($\alpha = 0.05$). When t-tests were done comparing perceived lateralization across all lead/lag delays for each listener, only one listener showed a significant difference between the 200- and 400-ms stimulus durations. There was no significant change in perceived lateralization between the 400- or 600-ms stimuli for any listener; the same was true for the data pooled across listeners.

C. Discussion

The results of experiment 2.2 clearly show that, up to ≈ 200 ms, stimulus duration can affect localization results for lead/lag stimuli with diotic onsets and offsets. Interestingly, this runs counter to the finding of Yost (2016), who found that for a single sound source presented in free field, duration did not impact sound source localization accuracy. This is likely because Yost presented simple stimuli (i.e., not lead/lag) where increased duration would offer no further information. For more complex stimuli, the auditory system may use increased duration to reduce uncertainty in the final decision variable.

Overall, the results of experiments 2.1 and 2.2 largely support the findings of Dizon and Colburn (2006), but there are some unexpected differences. For the diotically windowed stimuli in the present study, lateralization to the lead only occurs, on average, for lead/lag delays of up to 3 ms, whereas Dizon and Colburn (2006) show perceived

lateralization to the side of the lead well above chance for lead/lag delay as large as 10–20 ms. There are several possible reasons for these different outcomes.

First, the stimuli used by [Dizon and Colburn \(2006\)](#) were 500-ms duration, versus 200-ms in the current study. However, the results of experiment 2.2 show very similar results for stimulus durations of 200, 400, and 600 ms, suggesting that differences between results of the current study and [Dizon and Colburn \(2006\)](#) are not likely the result of different stimulus durations.

Second, while stimuli with a center frequency of 500 Hz are presented in both studies, the “wideband” condition in [Dizon and Colburn \(2006\)](#) is low pass filtered at 1500 Hz, whereas stimuli in the present study are bandpass filtered so as to have a frequency range of 100–900 Hz. Pilot testing (not shown) used noise stimuli with the same diotic onsets and offsets and 800 Hz bandwidth as the data tested in experiment 2.2, but center frequencies of 750 and 1000 Hz. Results showed perceived lateralization for the 1- and 4-ms lead/lag delay conditions that were approximately half-way between the results for experiment 2.2 and the midline, and at the midline for 5-ms lead/lag delay. For the 1000-Hz center frequency condition, only the 1-ms lead/lag delay condition resulted in normalized lateralization to +0.5; for all other lead/lag delays performance was at the midline. Lateralization at both center frequencies for the 1-ms lead/lag delay condition was likely the result of the large ILD that results from interference between lead and lag in each channel. While these pilot results informally suggest that the increased bandwidth of the [Dizon and Colburn \(2006\)](#) stimuli is also not responsible for differences in the results reported here and those of [Dizon and Colburn \(2006\)](#), their “wideband” stimuli were not tested in the current study, so no solid conclusion can be made in this respect.

Third, [Dizon and Colburn \(2006\)](#) recorded “sidedness” whereas the current study recorded the pointer ILD matching listeners’ perceived lateralization. If sidedness is recorded, then a fused (or unfused) perceived sound source would be registered as to the lead side if its intracranial position is even slightly to the lead side. For a non-fused auditory event, which could take the form of a split-image or a diffuse “sound-cloud,” if the overall balance of the stimulus is perceived to be in favor of the lead, then this too would be expected to result in perceived lateralization to the side of the lead. The current study recorded lateralization only for stimuli that were, based on extensive piloting, expected to be within the range of “fusion.” These differences in method could account for the extended range of localization dominance reported in [Dizon and Colburn \(2006\)](#).

VIII. MODELING ANALYSES

A. Motivation

Interactions that occur at stimulus onset have often been emphasized to provide explanation for the precedence effect ([Houtgast and Plomp, 1968](#); [Zurek, 1980](#); [Zurek and Saberi, 2003](#)). This may be, at least in part, because most testing of the PE has focused on click stimuli [but see [Braasch et al. \(2003\)](#), [Houtgast and Aoki \(1994\)](#), and [Rakerd and](#)

[Hartmann \(1986\)](#) for longer stimuli]. Onset dominance (OD), in the sense of spatial cues at stimulus onset dominating the perceived laterality of an entire auditory event, is commonly observed in auditory localization—e.g., [Kunov and Abel \(1981\)](#), [Saberi and Perrott \(1995\)](#), and [Freyman et al. \(1997\)](#). As such, OD is most commonly conceived of as applying globally to the entire stimulus and can be observed at surprisingly long time scales [e.g., the Franssen effect—[Franssen \(1960\)](#); [Hartmann and Rakerd \(1989\)](#)]. The duration [e.g., [Freyman and Zurek \(2017\)](#)], consistency of directional cues [e.g., [Freyman et al. \(2010\)](#); [Freyman et al. \(1997\)](#)], similarity of tokens within trains of noise bursts ([Stecker, 2018](#)), and reverberation ([Stecker and Moore, 2018](#)) all appear to vary the degree of OD for long-duration stimuli. Recently, [Stecker \(2018\)](#) has shown evidence that onset dominance may also work at the local level of stimulus envelope fluctuations within individual filters and may be important to explaining the ongoing PE.

The experimental conditions presented in this paper were aimed at providing the data to answer several inter-related, larger questions. First, if between-subjects differences in onset dominance might explain apparent differences in listener responses, what processes contribute to this onset dominance and what could determine or influence the weighting of cues at onset versus ongoing stimulus portions? Second, do the same monaural, peripheral mechanisms that have been used to account for many PE data using transient stimuli also explain the PE with longer duration stimuli, especially in terms of the ongoing PE?

Our modeling analysis attempts to answer these questions using simple mechanisms related to transduction (auditory periphery) and cue extraction (brainstem/midbrain) that all appear to contribute to OD at both local (e.g., individual amplitude fluctuations in the output of the auditory nerve) and global (e.g., the overall stimulus) time scales. We conceptualize OD not as a mechanism or “force” but rather as an observed outcome.

The auditory nerve model (AN model) of [Zilany et al. \(2014\)](#) includes various linear and non-linear mechanisms of peripheral processing (discussed below) that allow the examination of peripheral, monaural interactions that [Hartung and Trahiotis \(2001\)](#) and others (e.g., [Bianchi et al., 2013](#); [Trahiotis and Hartung, 2002](#); [Xia and Shinn-Cunningham, 2011](#)) have shown to be important contributors to the PE. Figure 8 shows output, in the form of mean firing rate, from the AN model in response to 50-ms duration sinusoids with 20-ms \cos^2 on and off ramps. It is clear that the neural response envelope is quite different to the stimulus envelope. Neural adaptation attenuates response amplitude after a few cycles. Hair-cell compression also shapes the pattern of modeled neural output, though this is not obvious in Fig. 8. The auditory periphery responds to stimulus amplitude in a roughly logarithmic fashion, and neural response only begins above a certain input threshold, so the rise-time of the response envelope fluctuation is sharp at onset. The envelope of neural output declines gradually after stimulus offset because of ringing of the basilar membrane. Together, these linear (filter ringing) and non-linear (compression and adaptation) aspects of peripheral auditory response create an

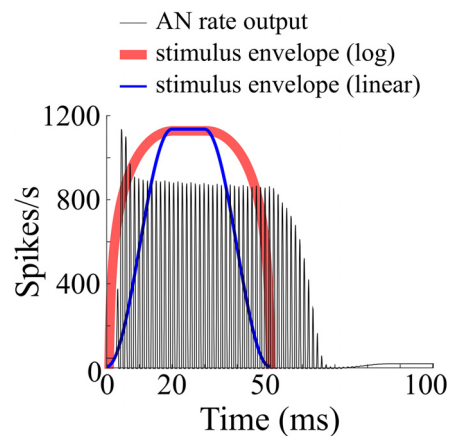


FIG. 8. (Color online) Output from the Zilany *et al.* (2014) AN model in response to a 70 dB, 50-ms duration 750 Hz pure tone with 20-ms \cos^2 on- and off-ramps showing effects of adaptation, and filter ringing. The envelope of the input sinusoid is shown at the same time scale as the neural outputs and arbitrary units of linear (thin line) and logarithmic (thick line) amplitude. Effects of hair-cell compression are not shown; the change in neural output brought about by an increase in stimulus amplitude of 6 dB (the approximate increase in amplitude from adding a lag to the lead stimulus) would barely be visible in this figure.

asymmetric internal envelope that is not the same as the stimulus envelope. These distinctions between response and stimulus envelope are critical for understanding the *internal* fluctuations in neural representation of concurrent (e.g., PE) stimuli and the effects of their interactions on overall ITDs/ILDs. For example, wavefronts arriving after the lead, when auditory nerve response to the stimulus has reached the point of compression/saturation, may have less of an effect on the overall stimulus envelope and therefore be less likely to produce a positive “onset slope” at that time in the stimulus, decreasing the chances that the lag ITD will be encoded. Adaptation may also result in enhanced response to the lead relative to the lag, especially at stimulus onset for longer lead/lag delays.

Dietz *et al.* (2013) and Dietz *et al.* (2014) [also see Gai *et al.* (2014)] have shown that fine-structure ITDs are primarily encoded during the rising slope of *stimulus envelopes* for relatively slow rise times of ≈ 40 ms. Stecker (2018) showed that, for sinusoidally modulated noise-burst trains, ITDs of clicks during the rising portion of each modulation period were most heavily weighted, even when the amplitude of subsequent clicks was greater. Zurek (2017), Freyman *et al.* (2018), and Stecker (2018) have suggested that the extraction of ITDs from rising slopes of the neural output are likely to be important to understanding the mechanisms underlying the ongoing PE. Our analysis built upon these earlier observations, emphasizing especially that the extraction of ITDs from the rising slopes of fluctuations in auditory nerve output is heavily affected by linear and non-linear response properties of the auditory periphery, as shown in Fig. 8. The dominance of fine-structure binaural information in the rising slope of stimulus individual envelope modulations can be thought of as a local, short-term onset dominance (see also Stecker, 2018). We further note that peripheral processing within the relatively narrow

auditory filters can introduce envelope fluctuations in AN output even in stimuli that have a relatively flat envelope, such as the noise stimuli presented in this paper.

B. Approach

ITD information in afferent activity was extracted from the time-varying mean rates of the AN model outputs in response to PE stimuli presented at 70 dB SPL. The model extracts the peaks of individual cycles (above a threshold of 20 spikes/s) of the firing rate functions of the left and right ANFs.

For ITDs, we computed the difference in peak time between left and right ANF responses on a cycle-by-cycle basis. We separated out ITDs that occurred when the slope of the envelopes of *both* left and right modeled auditory nerve outputs were rising (ITD_{RS}). The envelope of the AN model response was constructed using the extracted rate peak positions with the spline fit function in MATLAB[®]. Since only the peak rate per cycle was used, the extracted ITDs are free of explicitly imposed neural mechanisms for coincidence detection (e.g., coincidence window) and are not affected by the degree of temporal synchrony in afferent activities which normally dictate the width of the cross-correlation function and therefore the extraction of ITDs.

Three ITD estimates were made for each of ten modeled auditory filters spaced apart by equivalent rectangular bandwidths, as specified by Glasberg and Moore (1990): (1) “all ITDs,” estimated for all peaks in the response rate functions, regardless of the slope of the envelope of the modeled auditory nerve output, (2) “onset ITD_{RS} ,” estimated from only the first rising envelope slope at the onset of the entire stimulus, and (3) “ ITD_{RS} ,” integrated across the accumulated ITD_{RS} that occurred after stimulus onset during the ongoing stimulus portion. The weighted mean/standard deviation of each of these three ITD estimates was calculated across the ten modeled auditory bands using the $q(f)$ ITD weighting function from Stern *et al.* (1988), which approximates the relative saliency of ITDs for low-frequency stimuli across frequency as reported by Raatgever (1980).

To estimate long-term ILDs, a MATLAB implementation [Slaney (1998) of the gammatone filterbank of Patterson *et al.* (1995)] was used with the same filter center frequencies as those used for the AN model. ILDs were estimated as the dB energy ratio of the left and right outputs for each filter, $10 \log_{10}(E_{Li}/E_{Ri})$. ILDs were then mapped to ITDs so that they could be combined with ITD estimates. Yost (1981) showed that perceived laterality in response to sinusoids presented over headphones with ILDs were relatively uniform across frequencies, even at low frequencies. Furthermore, perceived laterality was essentially a linear function of ILD until ≈ 17 dB, at which point it became an increasingly compressive function. An error function was tuned so that an ILD of 5.2 dB mapped to an ITD of 300 μ s, based on the mean results across listeners from the reference condition used for normalizing individual listener data. ILDs were therefore mapped to ITDs as

$$\text{ITD}_{ILD_i} = \frac{2}{\sqrt{\pi}} \int_0^{ILD/19.1} e^{-t^2} dt, \quad (1)$$

where ITD_{ILD_i} is the ILD for some filter i mapped to an ITD value. The converted ILDs were then integrated across frequency using the same $q(f)$ weighting function used for ITDs, motivated by the finding in [Pastore and Braasch \(2015\)](#) that ILDs around 750 Hz appeared to have the greatest effect on the behavioral results. Note that since it is not clear exactly how ILDs can best be modeled using the outputs of the AN model, the ILD estimates used in this paper should be considered only as a first-order approximation of the internal representation of ILDs in the binaural display.

C. ITD estimates within a single filter, over time (peripheral mechanisms and cue extraction)

For an initial understanding of contributions of peripheral processing to the PE, we focus on an auditory band centered at 750-Hz. [Pastore and Braasch \(2015\)](#) found that binaural differences in this frequency region were reasonably predictive of the general behavioral trends identified in the data.

1. 1_0 vs 41_{20} conditions

Figure 9 shows modeling analyses for the 1-ms lead/lag delay, 0-dB lag level condition. For each stimulus, the top panel shows the rate responses of the 750-Hz ANF and its envelope and the bottom panel shows a binaural coincidence detection analysis. Examining first the 1_0 condition (top two panels), the ringing of the basilar membrane essentially merges the ANF response to the lead/lag stimulus pair in each ear, despite a delay (1.3 ms in the lead-side ear, 0.7 ms in the lag-side ear) between lead and lag stimuli.

The ITDs calculated during the rising slopes (ITD_{RS}) of both sides (filled circles) correlate well with listener responses to the lead side, whereas the ITDs calculated during other stimulus portions (open circles) do not. The mean values of ITDs, shown with arrows on the right of the figures, also confirm this.

Analyses for the 41_{20} stimulus, which has 20-ms onsets and offsets as opposed to the sharp rise and decay of the 1_0 stimulus, are shown in the bottom two panels of Fig. 9. Listeners reported a perceived lateral position that was closer to the lead ITD for the 41_{20} than the 1_0 stimulus. The rising slope ITD_{RS} captures this difference [i.e., comparing the mean ITD_{RS} in Figs. 9(A) and 9(B)].

As shown by [Pastore and Braasch \(2015\)](#) for the 200_{20} stimuli in the 764-Hz filterband, the ILD created by physical interference of lead and lag before arriving at the listener's ear was rather large at ≈ 16 dB. This interfering ILD not only appears to have “pulled” listeners' perceived lateralization towards the lead, but also had an effect on the ITD itself by advancing the threshold crossing time (i.e., discharge times) of the ANF on the side with a larger ILD. This is an example of how complex monaural peripheral interactions can shift the values of ITD and ILD away from those that were in the original stimulus. This interaction will, in turn,

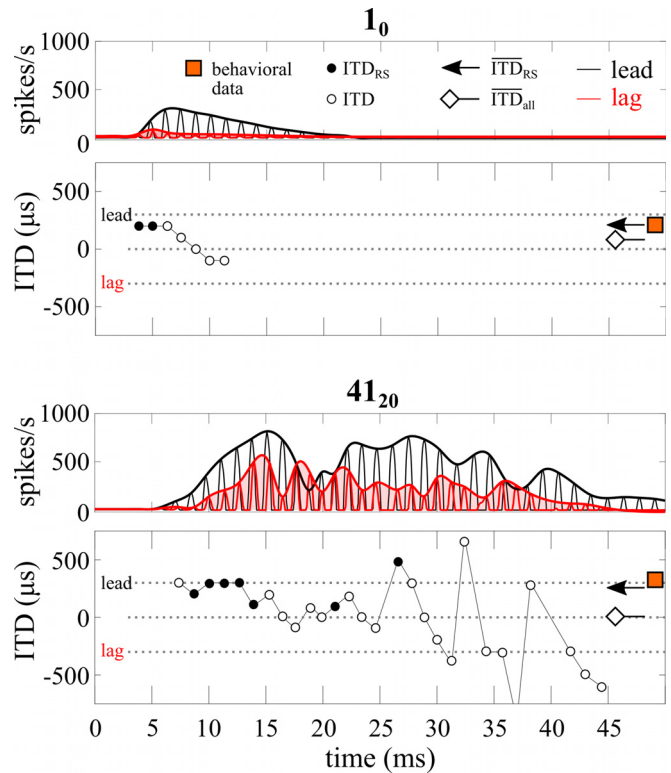


FIG. 9. (Color online) Modeling analyses for the 1-ms lead/lag delay, 0-dB lag-level condition for the 1_0 stimulus (top 2 panels) and the 41_{20} stimulus (bottom 2 panels). For each stimulus, modeled auditory nerve output for the auditory filter centered at 750 Hz, for the lead- and lag-side ears, is shown in the upper panel and a binaural coincidence detection analysis is shown in the lower panel. For each ITD analysis, ITDs calculated from the rising slope (ITD_{RS}) of the modeled auditory nerve output are shown with filled circles and other calculated ITDs are shown with empty circles. To the right side of each ITD analysis panel, the mean ITD_{RS} is shown with a filled, black arrow, and the mean of all ITDs (i.e., filled and empty circles), regardless of slope, is shown with an empty, diamond-shaped arrow. Mean behavioral data for the same conditions are shown with shaded squares.

produce variability in the ITD estimate across filters, which we will argue plays an important role in the relative weighting of ITDs from different stimulus portions.

2. 200_{20} vs 200_{20D} conditions

The following analysis suggests that large envelope fluctuations of the auditory nerve output within an auditory filter could function in an “onset-like” manner [also see [Stecker \(2018\)](#) and [Stecker and Diedesch \(2015\)](#)] to create a succession of local ITD estimates that could then be integrated over stimulus duration and weighted against the local ITD estimate at stimulus onset, thus accounting for the “ongoing PE” with the same basic mechanisms put forth by [Hartung and Trahiotis \(2001\)](#).

As we might expect, ongoing ITD_{RS} estimates are very similar for both the 200_{20} and 200_{20D} stimuli (see Fig. 11). Therefore, the modeling results for the 200_{20} stimulus shown in Fig. 10, allow us to consider ITD cues at both the onset of the 200_{20} stimulus and the ongoing ITD_{RS} for both stimuli. Lead/lag delays of 2 and 5 ms at 0-dB lag level are chosen because they yield similar results for the two stimuli at 2 ms lead/lag delay (strong localization dominance), but different

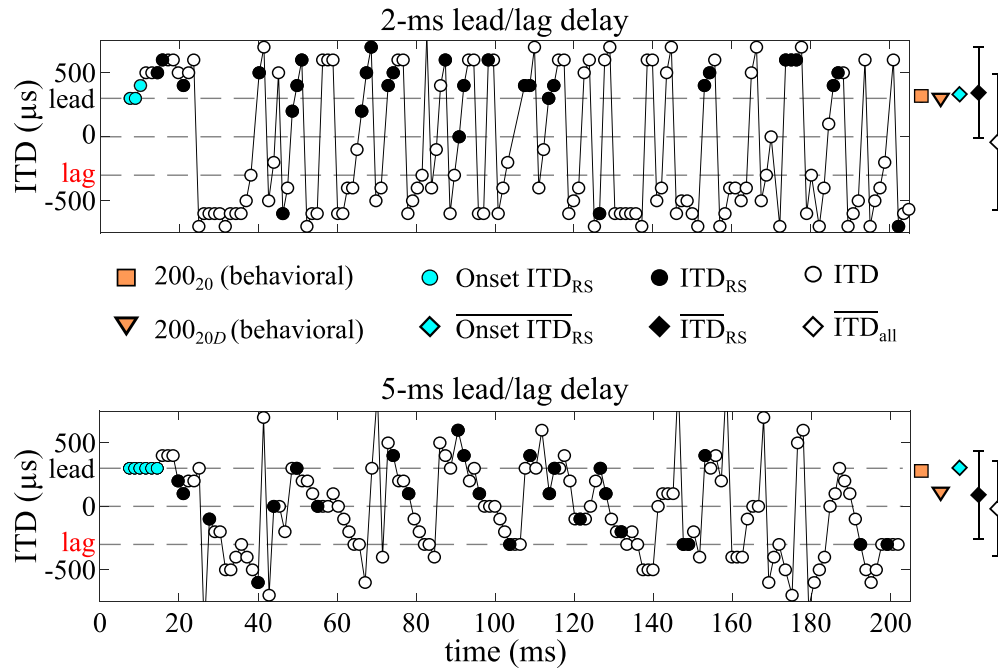


FIG. 10. (Color online) Detailed ITD analyses for the 200₂₀ stimulus, comparing the 2- and 5-ms lead/lag delay conditions at 0-dB lag level. Figure is read the same as Fig. 9, but mean ITD measures (diamonds) have error bars to indicate the standard deviation (across time), and are included at the right end of each figure panel along with the behavioral results for the 200₂₀ (shaded circles) and 200_{20D} (dotted windowed onset, inverted triangles).

results at 5-ms lead/lag delay (strong localization dominance for 200₂₀, weak for 200_{20D}).

The onset ITD_{RS} (shaded circles) are all very close to the lead ITD for both lead/lag delays, whereas the ongoing ITD_{RS} (black circles) are concentrated near the lead ITD for 2-ms lead/lag delay but fairly evenly distributed across ITDs for 5-ms lead/lag delay. Comparing the variability of the two types of ITD estimates, we might expect the onset ITD_{RS} estimate to dominate perceived laterality for the overall 200₂₀ stimulus. Comparing these ITD estimates to the behavioral data, it appears that responses to the 200₂₀ condition may be driven by onset ITD_{RS} whereas responses to the 200_{20D} condition may instead be driven by ongoing ITD_{RS}. Note that, as in Fig. 9, the ITDs estimated regardless of envelope modulations (open circles) average out to near zero, suggesting that these cues are largely ignored if they are encoded at all. Also note that at 5-ms lead/lag delay, ongoing ITD_{RS} are distributed very similarly to non-rising slope ITDs, whereas the two are quite differently distributed at 2-ms lead/lag delay.

Model output for the 2-ms lead/lag delay condition supports the idea that ongoing ITD_{RS} could be integrated to form an overall ITD estimate for the entire stimulus. That is, amplitude modulations are created as a function of the relatively narrow bandwidth of low-frequency auditory filters; this in turn creates a succession of onset-like portions of the auditory nerve output where ITD can be calculated on the rising slope of these modulations. On average, since the lead and lag are copies of each other, rising slopes will more often be dominated by the ITD of the lead, just as they are for short stimuli such as the 1₀ stimuli. Essentially, the apparent preference for ITD_{RS} filters out most ITDs that do not come from the first-arriving amplitude fluctuation, which

comes from the lead. As such, a succession of instances of local onset dominance are then accumulated over time to produce the ongoing PE.

As for the 2-ms lead/lag condition, the behavioral data for the 5-ms lead/lag, 200₂₀ condition are well-matched by the mean onset ITD_{RS} and the data for the 200_{20D} condition are well-matched by the mean ongoing ITD_{RS}. In speculating why localization dominance is quite weak at 5-ms lead/lag delay for the 200_{20D} stimulus, it seems likely that the time-course of adaptation at the level of the synapse between the inner hair cell and auditory nerve is worth considering. For example, adaptation in the modeled auditory nerve output (see Fig. 8) centered at 750-Hz appears to take hold after ≈ 3 cycles (3.9 ms)—one might speculate that, for stimuli with the dichotic stimulus onsets preserved, adaptation may then start to play an important role in emphasizing lead inputs that arrive 4 ms or more before the lag even arrives, therefore leading to increased localization dominance at lead/lag delays of 4 and 5 ms, even with increased lag level. It may also be that the decorrelation produced by longer lead/lag delays is important to understanding why the mean ongoing ITD_{RS} for the 5-ms lead/lag delay stimulus only weakly favors the lead.

D. ITD estimates across filters (onset vs ongoing ITDs)

Figure 11 shows modeled ITDs for all tested lead/lag delays at 0-dB lag level for the 200₂₀ (top row) and 200_{20D} (bottom row) stimuli. We calculated three types of ITD estimates for ten modeled auditory filters spaced one Equivalent Rectangular Bandwidth apart, at the same center frequencies as those analyzed in Pastore and Braasch (2015). The figure panel entitled “ITD Weighting” shows the $q(f)$ ITD

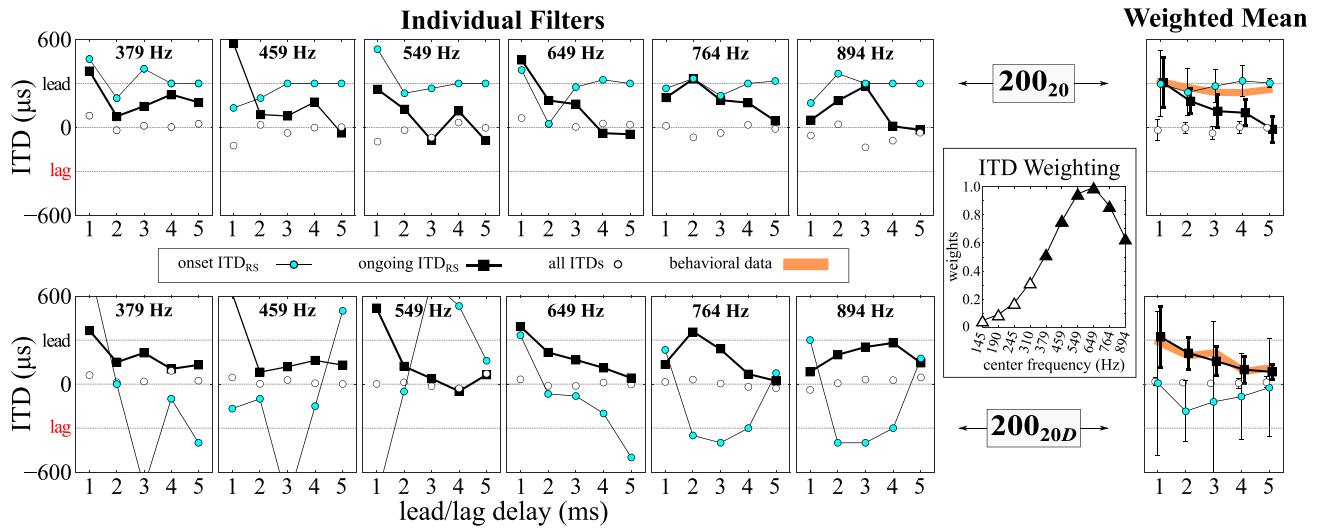


FIG. 11. (Color online) Modeled ITDs for the 200₂₀ (top row) and 200_{20D} stimuli (bottom row) at 0-dB lag level. Shaded circles, connected by thin black lines, represent ITD_{RS} calculated during the first rising slope of the onset of the entire stimulus. Filled black squares show ITD_{RS} calculated from the rising slope of within-filter envelope fluctuations during the ongoing portion of the stimulus. Open, unconnected circles show ITDs estimated from all stimulus portions, regardless of slope. Panels to the left show model results for the individual filters most heavily weighted in the ITD weighting function (center panel—filled triangles indicate center frequencies for which model results are shown). The center frequency for each filter is shown at the top of each individual filter model panel. Modeled ITDs for these individual filters are then weighted by the ITD weighting function (see text for more details). The weighted mean and standard deviation across center frequencies of all ten individual filters are shown in the rightmost column along with the behavioral data (thick shaded line). Behavioral data are plotted so that an average normalized pointer ILD of $\pm 1 = \pm 300 \mu\text{s}$ (see Sec. II, reference condition).

weighting function from Stern *et al.* (1988). Filled triangles indicate those frequency bands that are weighted most heavily—model results for these filters are shown in the individual panels to the left. The right-most column shows the mean and standard deviation of all ten filters, weighted by the $q(f)$ function for each of the three forms of ITD estimate discussed below. It is important to note that the error bars in this figure (and the next) show variability of the mean ITD estimates across frequency, and *not* variability of each mean estimate over time.

The unlinked open circles show results for all ITDs averaged together, regardless of their temporal location in the stimulus. As in Fig. 10, the open circles indicate a position at or near the midline, and are not well correlated with the behavioral data. We therefore now focus only on rising slope ITD_{RS}. To investigate the extent of dominance of ITD cues encoded at the onset of the stimulus, a distinction is made between ITD_{RS} calculated during the very first contiguous rising slope at the onset of the entire stimulus (onset ITD_{RS}) versus all other ITD_{RS} estimates during the ongoing stimulus portion wherever low-frequency envelope fluctuations in the auditory nerve outputs within the auditory band give rise to a positive slope (ongoing ITD_{RS}). Several observations can be made comparing these estimates for the 200₂₀ and 200_{20D} stimuli.

Looking at the data for individual filters, the onset ITD_{RS} estimates (shaded circles) are fairly consistent across filters for the 200₂₀ condition (top row), whereas this same estimate fluctuates wildly across filters for the diotically windowed 200_{20D} condition (bottom row)—this difference in variability becomes clear in the weighted mean data when comparing the errorbars for the onset ITD_{RS}, showing the weighted standard deviation between filters, accompanying the shaded circles in the rightmost column. Perhaps

relatedly, the mean onset ITD_{RS} estimate across filters correlates well with the behavioral data for the 200₂₀ condition (top row, right-most column), and quite poorly for the 200_{20D} condition (bottom row, right-most column).

The filled black squares indicate ongoing ITD_{RS} estimates. First, while ongoing ITD_{RS} does a poor job of predicting listener performance for the 200₂₀ condition, it correlates quite well with the 200_{20D} behavioral data. It appears that the ITD_{RS} from the initial portion of the stimulus is largely ignored in favor of an estimation based on the accumulation of a succession of instances of ITD_{RS} that occur with narrow-band amplitude fluctuations of the auditory nerve output within and across filterbands. This ongoing ITD_{RS} estimate predicts the weak localization dominance observed in the behavioral data for the 4- and 5-ms lead/lag delay conditions, and is quite similar for both the 200₂₀ and 200_{20D} conditions, as could, perhaps, be expected. Note that the construction of these two different stimuli used different portions of the same sample of noise, demonstrating that the model does not rely heavily on the particular noise sample that is used (the model was also run on many other noise samples with very little impact on performance, consistent with the behavioral results of Pastore *et al.*, 2016).

Given that the ongoing ITD_{RS} estimate is essentially the same for both the 200₂₀ and 200_{20D} conditions, we might ask “why does the onset ITD_{RS} estimate predict perceived laterality for the 200₂₀ condition and not the 200_{20D} condition, and why is the opposite true for the ongoing ITD_{RS} estimate?”

We may hypothesize that the variability of each of these estimates influences their relative weighting at central “decision making” levels. While this hypothesis appears to be supported in the lower 200_{20D} row, the upper 200₂₀ row shows the ongoing ITD_{RS} estimate as less variable than the onset ITD_{RS} estimate, but this is unlikely to be the case,

because the variability (across frequency channels) of the estimate over stimulus duration shown in Fig. 10 is not included in the error bars, which only show variability of the mean estimates across frequency. For example, calculations from Fig. 10 of the variability of onset ITD_{RS} within a single filter centered at 750 Hz, reveal that the standard deviation of ITD_{RS} at stimulus onset is 39.6 μ s, averaged across lead/lag delays, while this same measure is 157 μ s for the 200_{20D} conditions and 361 μ s across all stimuli tested in experiment 2.2. That is, onset ITD_{RS} was \approx 10 times more variable for the stimuli with diotic onsets than for the 200₂₀ stimuli. While this modeling does not attempt to provide an explicit mechanism for how and where variability over time and across frequency might be integrated for use in central cue weighting and decision making, this will clearly be important to future modeling efforts.

E. Formation of a decision variable—Relative weights of onset/ongoing ITD and ILD

After spatial cues have been extracted, an overall estimate of laterality is likely to involve weighting of cues or local estimates of laterality at some central level of processing. Such weighting would probably involve comparison of ITD versus ILD cues within individual filter bands, comparisons of these cues across frequency, and spatial estimates from stimulus onset versus other local estimates from the ongoing stimulus portion. At each of these levels of comparison, we might expect relative weighting to be influenced or determined by the variability of each estimate so that estimates with low variability are weighted to a greater degree than highly variable estimates. Furthermore, there may be intrinsic biases, such as for ITDs over ILDs [e.g., Wightman and Kistler (1992)], or cues at stimulus onset over later arriving cues.

Figure 12 shows model results, integrated across filters, for the 200₂₀, 200₅, and 200_{20D} stimuli for all combinations of lead/lag delay and lag level. Figure panels are read the same as the right-hand column in Fig. 11, but ILDs, integrated across frequency and then converted into ITDs according to Eq. (1) (diamonds), are now included as well. To simplify the figure, mean values for the ITDs extracted without regard to the slope of the output of the auditory nerve do not have error bars. Note that, like Fig. 11 error bars only include the variability of the ITD estimates across frequency, and do not show their variability over time, unlike Figs. 9 and 10. While both types of variability are likely to be important, we simply assume that the variability of the ongoing ITD_{RS} will generally be greater than the onset ITD_{RS} , at least for stimuli with dichotic onset cues. This is likely to be the case for most if not all conditions, and this may increase the relative weighting of ITDs extracted at stimulus onset in general. Error bars are also not shown for ILD estimates to simplify the figure, because ILDs were not calculated from the outputs of the AN model (it is not clear how to do this properly), and because it is unclear how to properly compare variability between ITD and ILD.

Several trends emerge for the 200₂₀ results (Fig. 12, top row). First, onset ITD_{RS} correlates quite closely with the

data for the 200₂₀ stimulus for lag levels of 0–4 dB. At greater lag levels, the onset ITD_{RS} estimate is actually closer to the lead position than the behavioral data. Second, as lag level increases, the onset ITD_{RS} for 1 and 3 ms lead/lag delays are closer to midline than estimates at the other lead/lag delays. Third, the variability across frequency of the onset ITD_{RS} (called “spectral incoherence”) is usually comparable to that for the ongoing ITD_{RS} estimate. Fourth, there is a large ILD pointing to the lead for the 1 ms lead/lag delay at all lag levels. This ILD appears to “pull” listener responses toward the lead position. The very high spectral incoherence of the onset ITD_{RS} estimate at 1 ms may help account for the size of the effect of the ILD at this delay. Overall, it appears as though onset ITD_{RS} drives listener responses for lag levels of 0–4 dB (with the ILD at 1-ms lead/lag delay contributing more to perceived laterality as lag level increases). For lag levels >4 dB, the contribution of the ILD, and perhaps the ongoing ITD_{RS} estimate (which is less variable across frequency than onset ITD_{RS}) appears to increase.

Looking at the 200₅ results (Fig. 12, middle row), we see that, as expected, ILDs and ongoing ITD_{RS} are nearly the same as for the 200₂₀, but onset ITD_{RS} is much more reliably at the lead ITD and is far less variable across frequency. Also, onset ITD_{RS} correlates quite closely with the data for lag levels of 0–4 dB. At greater lag levels, the onset ITD estimate is actually closer to the lead position than the behavioral data. For lag levels >4 dB, the contribution of the ILD, and perhaps the ongoing ITD_{RS} estimate (which is less variable across frequency than onset ITD_{RS}), appears to increase.

The 200_{20D} are shown in the bottom row of Fig. 12. As expected, ILDs and ongoing ITD_{RS} are nearly the same as for the 200₂₀, but onset ITD_{RS} is shifted down to the midline and lag side, and the onset ITD_{RS} estimate is far more variable across frequency for lag levels \leq 4 dB. For the 0-dB lag level, it appears that ongoing ITD_{RS} are the primary drivers of listener responses. For lag levels >0 dB, the contribution of the ILD appears considerable. At lag levels of 8 and 10 dB, the ongoing and onset ITD_{RS} estimates begin to converge, and perceived lateralization is approximately the average of the ITDs versus the ILDs. Across all three stimulus conditions, the difference between ongoing ITD_{RS} and ITDs extracted from non-rising slopes largely disappears for lag levels >2 dB.

Pastore and Braasch (2015) showed that, for the 200₂₀ stimulus, variability of the ITD estimate across frequency bands, called “spectral incoherence” (Blauert, 1997, p. 346), increased with increasing lag level. For the three stimuli modeled in Fig. 12, spectral incoherence within any given lag level is greatest at 1-ms lead/lag delay, and decreases with increasing lead/lag delay. For example, for the 200₅ stimulus, the onset ITD_{RS} estimate is an average (across lag levels) of 3.51 times more variable across frequency at 1 ms lead/lag delay than at 5 ms lead/lag delay. This same ratio is 5.96 for the 200₂₀ stimulus and 1.83 for the 200_{20D} stimulus. The same ratio for the ongoing ITD_{RS} estimate for the 200_{20D} stimulus is 2.55. This may help to explain why the ILD at 1 ms has such an outsized effect on perceived laterality, and, as the spectral incoherence increases with lag level,

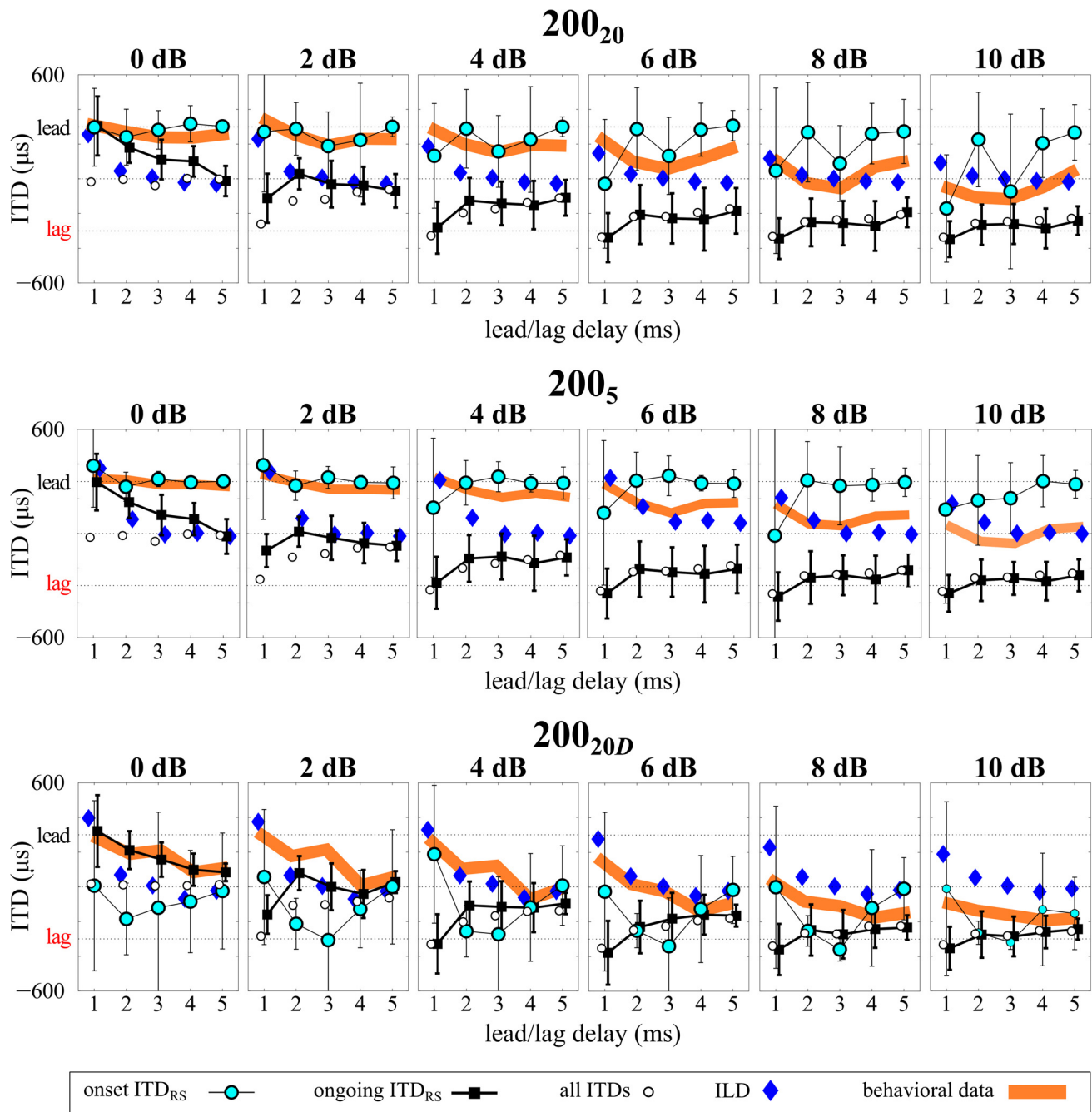


FIG. 12. (Color online) Modeling results, integrated across frequencies, for the 200_{20} (200-ms duration, 20-ms \cos^2 onset/offset slopes), 200_5 (200-ms duration, 5-ms \cos^2 onset/offset slopes), and 200_{20D} (200-ms duration, 20-ms \cos^2 diotic onset/offset slope) stimuli at all presented combinations of lead/lag delay and lag level. The same types of ITD estimates are shown as in Fig. 11, with the addition of estimated long-term ILDs (shaded diamonds). As in Fig. 11, behavioral data are shown with the thick shaded line; the thickness of the line is approximately the same as the average standard deviation of the behavioral data.

why the effect of ILDs in general seems to increase with increased lag level.

In the onset ITD_{RS} estimates for the 200_5 stimulus we see evidence that the onset slope affects the value of ITDs extracted at the onset of the stimulus and their variability across frequency. Note that the onset slope will have no effect on ITDs and ILDs extracted from the ongoing portion, as the model demonstrates. In considering what may determine the relative weighting of onset versus ongoing ITD_{RS} ,

and in turn, the weighting of the ITD estimate by the ILD estimate, we may speculate that the variability of these estimates could be an important factor.

For the 200_{20D} stimulus, the ratio of the variability between the ongoing versus onset cues increases with lag level—at 0 dB the ratio is 0.32 (the ongoing estimate is only a third as variable as the onset estimate), but it has more than tripled, to 1.12 at 10 dB lag level (the two estimates are roughly the same variability across frequency). This supports

what we might intuit as we compare these estimates to the behavioral data for the 200_{20D} stimulus: the ongoing ITD estimate appears to account for less and less of listeners' perceived laterality as lag level increases.

Comparing across stimuli, averaged across all combinations of lead/lag delay and lag level, the spectral incoherence of the onset ITD_{RS} estimate for the 200_{20D} stimuli was 26% greater than for the 200₂₀ stimuli. On the other hand, this same type of comparison revealed that the onset ITD_{RS} estimate for the 200₅ stimuli is 22% less variable across frequency than for the 200₂₀ stimuli. Comparing the ongoing versus onset ITD_{RS} estimates for the 200_{20D} stimuli, the ongoing estimate is an average (across all conditions) of 57% less variable across frequency than the estimate at stimulus onset, supporting the idea that the relative variability of the onset and ongoing ITD estimates at least partially determines their relative weighting and thus the degree of onset dominance at the overall level of the stimulus. Comparing modeled cues to the behavioral data also supports the idea that ITDs dominate perceived laterality, but ILDs are weighted increasingly as the ITD estimate becomes more variable across frequencies and over time.

IX. GENERAL DISCUSSION

A. Relation of the modeling analyses to previous work

Freyman and Zurek (2017) compared the strength of onset and ongoing cues by presenting a single onset click followed by trains of lead/lag pairs of clicks with either alternating or consistent ITDs. In a condition where the onset click pair had an ITD of 0 μ s, a click train of \approx 30 ms was required for listeners to lateralize the overall stimulus close to the ITD of the lead in the alternating lead/lag click train that followed the diotic onset. Performance for the condition where the ITD of the click pairs did not alternate (i.e., all clicks had the same ITD as the lead in the alternating ITD condition) elicited very similar behavior on a very similar time scale, suggesting that the ongoing PE is quite robust at 2-ms lead/lag delay and can robustly “restart” after a 4-ms pause between lead/lag click pairs. For the long-duration noise stimuli tested here, it appears that more integration time was necessary to produce localization dominance. This fits with the idea that the slower “onsets” of large amplitude fluctuations (as compared with rectangular clicks) that could be used for “restarting” the PE in individual auditory bands that would be presented in the noise stimuli would produce a weaker ongoing PE, therefore requiring greater integration time for localization dominance to emerge.

Stecker and Hafter (2002) investigated the relative influence of onset and ongoing portions of precedence stimuli made from click trains and found that the onset dominated perceived lateralization when the interval between the clicks was less than 5 ms. As the interval between the clicks was increased beyond 5 ms, the binaural cues carried by the clicks were weighted relatively uniformly over stimulus duration—also see Saberi and Perrott (1995). This result appears to be in keeping with the time scale of peripheral interactions discussed in Sec. VIII A. The modeling analyses support the idea that large envelope fluctuations in the neural output of individual auditory filters function in an “onset-

like” manner if they are spaced far enough apart in time (perhaps 4–8 ms) [e.g., Stecker (2018); Stecker and Diedesch (2015)], thus facilitating the extraction of ITDs. The succession of local ITD estimates would be likely to favor the lead *more often* than the lag. Integrating these estimates over stimulus duration would result in localization dominance, thus accounting for the “ongoing PE” in a way that includes the effects of monaural, peripheral processing (e.g., adaptation, compression, and ringing of the basilar membrane) as put forth by Hartung and Trahiotis (2001) and analyzed in Sec. VIII. As such, it does not appear that a separate “ongoing PE” mechanism is required to describe our data, but rather just a re-weighting of ongoing ITD cues relative to those at stimulus onset. It appears that the relative variability of these two estimates has considerable impact on this re-weighting.

Freyman *et al.* (2018) show evidence that the peripheral interactions that predict the PE for clicks may not fully account for the “ongoing PE.” Specifically, the lag clicks in a monaural click train appear not to be energetically masked as one might expect based on the idea that monaural, peripheral interactions lead to some kind of “lag suppression.” In this regard, it is worth noting that Hartung and Trahiotis (2001) wrote of the effect monaural, peripheral processes would have on binaural difference cues, and that these effects are important to consider when attempting to attribute the PE to later processes—Hartung and Trahiotis (2001) were explicit that they did *not* consider their model to imply “lag suppression.” In keeping with this, Freyman *et al.* (2018) suggest that the ITD of the leading click pairs in an ongoing click train are emphasized as opposed to the lag being “suppressed.” This interpretation is supported by Braasch and Pastore (2018), who, using a precedence-based spatial release from masking paradigm, found that the PE for long-duration noise stimuli is unlikely to be the result of any perceptual “removal” or “suppression” of the lag (see also Freyman *et al.*, 1999).

Freyman *et al.* (2018) point out that the findings of Dietz *et al.* (2013) and Dietz *et al.* (2014), who found that “the auditory brain uses binaural information in the stimulus fine structure only during the rising portion of each modulation cycle,” suggest that a model that uses rising envelopes to preferentially encode ITDs would hold promise in explaining the ongoing PE (see Zurek, 2017, for modeling efforts that consider some, but not all, of the issues presented in our analyses here). The results and analyses of Stecker (2018) with click trains also offer strong support for such an approach. The modeling in this report supports these points: this model does not include any mechanisms specifically devoted to “echo suppression” or “lag removal” [e.g., Braasch (2013), (2016); Lindemann (1986)]. A fuller implementation may, however, benefit from inhibition as, for example, implemented by Xia *et al.* (2010), to better account for listener performance at higher lag levels.

Grosse *et al.* (2017) have reported data showing that the relative consistency of binaural difference cues, especially ITDs, across frequency [i.e., “straightness,” see Stern *et al.* (1988)] in the lead and lag stimuli is an important factor in the PE. The modeling in this paper supports this idea. The variability of ITDs across frequency at stimulus onset, before

the lag stimulus arrives, is naturally quite low. When the lag arrives, it combines and interferes with the lead on the basilar membrane (and before arrival at the ears for long-duration, temporally overlapping stimuli), considerably increasing the variability of ITDs and ILDs across auditory filters. As such, the relatively higher “straightness” of the binaural display associated with the lead before the lag arrives (stimulus onset) as compared to that associated with the combined lead and lag (the ongoing stimulus portion) is a natural outcome for lab-based, identical lead/lag stimuli, as well as room acoustic scenarios, even with early, highly coherent reflections [e.g., see [Blauert \(1997\)](#), Fig. 3.46, p. 276]. Regardless of whether any explicit mechanism for straightness exists or not, the relative difference in the “straightness” of the onset versus ongoing stimulus portions of PE stimuli seems important to understanding the PE.

The modeling analyses suggest that the weighting of cues involved in the PE would involve considerable complexity that is unlikely to be “hardwired.” It therefore seems worth considering that this cue weighting may be subject to learning. This observation is supported by developmental PE work such as [Clifton et al. \(1984\)](#) and [Litovsky \(1997\)](#), and may help to explain how different listeners could perceive the 200₂₀ stimulus so differently in [Pastore and Braasch \(2015\)](#).

B. Individual differences in onset dominance

Recall that ILDs which developed from physical interference of lead and lag across the ongoing portion of the stimuli appeared to have a large effect on the performance of some listeners and very little on others’ for the 200₂₀ stimuli presented in [Pastore and Braasch \(2015\)](#) and in experiment 1.1. The authors speculated that a possible reason for the high between-subjects variability is that some subjects are highly onset dominant and rely on this more in their processing of precedence stimuli, whereas others rely more on the ongoing portion. To investigate this, the onset was made more rapid to see if this changed lateralization differently between listeners. The hypothesis was that onset dominant listeners who rely primarily on onset cues would show a “benefit” (lateralize further to the lead position than for the 20 ms condition) when the onset cue was more rapid, whereas those who primarily use ongoing interaural cues might see very little benefit at all. Correspondingly, listeners who primarily rely on onset cues might be expected to show lateralization toward the median for the diotic onset/offset condition, whereas listeners who primarily use ongoing binaural cues would continue to perform as they had when 20-ms onsets were included in experiment 1 (assuming they lateralized to the lead in that experiment’s results). While detailed analyses of individual listeners’ data across all these conditions is not presented in this report, no such correlation was immediately obvious. That is, listeners’ performance on one stimulus condition did not appear clearly predictive of their performance on any other.

Looking back at the top row in Fig. 12, the pattern across lead/lag delays for the onset ITD_{RS} points to an unexpected possibility that complicates any correlation of onset dominance with listener results. In [Pastore and Braasch](#)

(2015), as compared to their average perceived lateralization across lead/lag delays, approximately half of the listeners’ responses for the 1-ms lead/lag delay was further towards the lead position, at 3-ms lead/lag delay their responses “dipped” further towards the lag position, and at 5-ms lead/lag delay their responses “rebounded” further towards the lead position. This pattern of “oscillatory” lateralization became increasingly pronounced with increased lag level. This same pattern across lead/lag delays and lag level is clear to see in the onset ITD_{RS} estimates shown in the top row of panels in Fig. 12 and is not present for the 200₅ stimulus shown in the middle row of panels in Fig. 12. This suggests that the oscillatory pattern observed in the responses of many listeners for the 200₂₀ stimulus may have been the result of *weak* OD so that ILDs near 750 Hz had an outsized effect on the overall laterality estimate, or the oscillatory pattern could be the result of a *high* degree of OD, resulting in the onset ITD_{RS} dominating perceived laterality of the overall stimulus.

Finally, it seems likely that inter-subject differences in their relative sensitivity and weighting of ITDs and ILDs, as documented by [McFadden et al. \(1973\)](#) and others, substantially complicates any attempt to determine the degree to which different listeners weighted cues at stimulus onset to any greater or lesser degree than cues from the ongoing stimulus portion.

X. SUMMARY

This report asked three related questions. First, how might onset dominance be involved in the mechanisms that produce the behavioral outcome called the precedence effect? Second, what underlying mechanisms influence or determine this relative weighting of cues from earlier vs later stimulus portions? Third, are mechanisms invoked to explain the PE for transient stimuli relevant to long-duration stimuli where the precedence effect appears to arise, at least partially, from the ongoing stimulus portion? To answer these questions, we presented targeted stimuli, ranging in duration from near-transient (1 ms) to long-duration (600 ms) with onsets ranging from rectangular to 20-ms cos² on-ramps, and manipulated lag level to reveal characteristics of the underlying PE mechanisms.

When the gating onsets of the overall stimulus were left intact, listeners demonstrated localization dominance that was robust to increased lag level, regardless of stimulus duration. Transient, 1-ms duration noise stimuli were most robust to increased lag level, and the effects of ILDs from the physical interference of lead and lag within the left and right channels appeared to increase with stimulus duration, supporting the notion that ILDs may be integrated over the duration of the stimulus, while ITDs near the gating onset of the stimulus are weighted most, supporting the conclusions of [Diedesch and Stecker \(2015\)](#). Faster onset slopes usually induced increased localization dominance and resistance to the effects of ILDs.

Applying a diotic window to the overall stimulus onset resulted in continued localization dominance, but only at lead/lag delays of 3 ms or shorter. Longer lead-lag delays

resulted in greatly decreased localization dominance, especially as the level of the lag was increased. For these diotically gated stimuli, longer stimulus durations enhanced the degree of localization dominance but increasing stimulus duration beyond 200 ms yielded very little increase in localization dominance.

Lead/lag delays in the range of ITDs that can be expected based on the size of the human head (less than $\approx 700\mu\text{s}$), resulted in performance that was less determined by the temporal order of the stimuli and more affected by ILDs.

We then analyzed these results using a model that incorporated monaural, peripheral effects such as filter ringing, compression, and adaptation at the synapse between the hair cells and auditory nerve. A simplified coincidence-detection model was then implemented (as opposed to the more-common cross-correlation analyses) and ITDs were extracted from stimulus portions where the slope of *both* left and right inputs were rising. This analysis of ITD extraction showed that data with relatively fast, dichotic onsets could be explained with ITDs extracted from the onset stimulus portion, and that stimuli with diotically windowed onsets were more closely predicted by ITDs extracted from the ongoing stimulus portion. We then considered the variability of the different ITD estimates in light of how they would be weighted against each other and in turn weighted with (or by) ILDs.

These modeling analyses show that monaural, peripheral interactions that are often invoked to explain results for transient lead/lag stimuli are relevant to explaining the precedence effect for long-duration stimuli, even though perceived lateral position is different for the two types of stimuli under some conditions. The modeling analyses also support the idea that the extraction of low-frequency, fine-structure ITDs from the rising portion of amplitude fluctuations of auditory nerve output within auditory filters may be an important factor underlying the precedence effect, and that these short-term, local ITD estimates can be integrated to demonstrate localization dominance during the ongoing stimulus portion. The modeling also showed evidence that onset dominance can be observed at several levels of processing, including monaural, peripheral levels, cue extraction, and the ultimate weighting of cues for an overall estimate of stimulus laterality. These processes all appear to affect the relative variability, over time and across frequency, of ITD and ILD estimates, and are therefore likely to strongly influence the cue weighting that, along with other variables such as listener strategy, results in the behavioral outcome we recognize as the precedence effect.

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APPENDIX: NORMALIZATION OF BEHAVIORAL DATA

Data points α_i to the left of the $0\text{-}\mu\text{s}$ reference position were normalized as described in Braasch *et al.* (2003): $y_i = (\alpha_i - \alpha_{0\mu\text{s}}) / (\alpha_{0\mu\text{s}} - \alpha_{-300\mu\text{s}})$, and data points α_i recorded to the right of the $0\text{-}\mu\text{s}$ reference position were normalized according to $y_i = (\alpha_i - \alpha_{0\mu\text{s}}) / (\alpha_{300\mu\text{s}} - \alpha_{0\mu\text{s}})$, where y_i is the normalized pointer ILD, $\alpha_{0\mu\text{s}}$ is the median ILD employed by a particular listener to match the intracranial position of the $0\text{-}\mu\text{s}$ reference stimuli, $\alpha_{-300\mu\text{s}}$ is the median ILD employed by that listener to match the intracranial position of the $-300\text{-}\mu\text{s}$ reference stimuli, and $\alpha_{300\mu\text{s}}$ is the median ILD employed by that listener to match the intracranial position of the $+300\text{-}\mu\text{s}$ reference stimulus.

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